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The Factors that Influence the Sensitivity of the Retina to Color: A Quantitative Study and Methods of Standardizing

By

GERTRUDE RAND, Ph.D.

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PREFACE.

The following study, practically as is here presented, was submitted to the Faculty of Bryn Mawr College in May 1911 in partial fulfillment of the requirements for the degree of Doctor of Philosophy. It is the outgrowth of a series of studies dealing with the phenomena of color vision that was begun in 1908 by the writer working under the direction of and in collaboration with Professor C. E. Ferree of Bryn Mawr College. In order to show in what way the present study, which deals with the formulation of a technique for investigating color sensitivity, is the logical outcome of the initial studies in the series, and is, moreover, required for the completion of the later studies, a brief résumé will be given of the work undertaken in the investigations preceding and following it.

The first of these studies entitled: *Colored After-image and Contrast Sensations from Stimuli in Which No Color Is Sensed,* was published in the *Psychological Review,* 1912, XIX, pp. 195-239. As is shown by the title, the article deals with the conditions under which colored after-image and contrast sensations may be aroused from stimuli in which no color is sensed. A formulation of these conditions, together with allied fusion and limen experiments, shows the phenomenon to be a peculiarity of the inhibitive action of brightness upon color. Brightness fused with color inhibits its saturation. With the exception of the region just within the limits of sensitivity for two colors, the following may be stated roughly as a law of this action for all colors and all parts of the retina: white inhibits most, grays in the order from light to dark next, and black least. This law was generalized from the results of fusion and limen experiments in a large number of meridians of the retina. In accord with this law, color may be obtained in the after-image when none is sensed in the stimulus when an unfavorable brightness quality is fused with the stimulus color and a favorable one with the after-image color. The technique for securing these conditions

for the after-image sensations in central and peripheral vision, for the contrast sensations in central vision, and for the phenomenon which we have called the Purkinje-Brücke phenomenon, is described in detail in the paper. But the study is not quantitative. The results do not show, for example, that the inhibition of the stimulus color has no effect upon the after-image. They show merely that, working near the limen, the stimulus color may be inhibited and the complementary color still be sensed in the after-image.

In order to determine as accurately as possible to what degree, if at all, the intensity of the after-image excitation is decreased by adding to the stimulus color a brightness excitation unfavorable to its saturation, the second study of the series was begun in 1909. It was entitled: *The Fusion of Colored with Colorless Light Sensation: The Physiological Level at Which the Action Takes Place.* An abstract of this article was published in the *Journal of Philosophy Psychology and Scientific Methods,* 1911, VIII, pp. 294-297. The full report will shortly be published in the *Psychological Review.* The results of this study have a twofold bearing. (1) They make plain once for all why it is possible to obtain color in the after-image when none is sensed in the stimulus, for they show that the intensity of the after-image excitation is not decreased at all by adding to the stimulus color a brightness excitation unfavorable to its saturation. (2) They throw some light on the broader problem presented by the fusion of brightness and color. By serving to indicate the level at which this action takes place, they help, for example, to explain a number of somewhat puzzling phenomena attendant upon the fusion of brightness with color, in case of positive, after-image, and contrast sensations. This action takes place apparently posterior to the seat of the after-image and contrast processes and the cancelling action of the complementary colors. There are two effects of the fusion of brightness with color, both of which are pressed into service in drawing the above conclusion: (1) it reduces the saturation of the color sensation; and (2) it changes the quality or tone of certain colors. This conclusion is based on the following lines of argument:

(1) When the color of the stimulus is inhibited by the addition of a brightness excitation, the intensity of the after-excitation, judged in terms of the duration of the after-image, is not affected by this excitation. (2) When the tone of the color aroused by a given stimulus is changed by the addition of a brightness excitation, the color of the after-image does not undergo a complementary change. (3) When the saturation of the inducing color is inhibited by the addition of a brightness excitation, the saturation of the contrast color is not affected by the change. (4) When the tone or quality of the inducing color is modified by adding a brightness excitation, the tone of the contrast color is not determined in the complementary direction. (5) When a given color is inhibited by the addition of a brightness excitation, its power to cancel the complementary color is not altered. (6) When the tone or quality of a color is altered by the addition of a brightness excitation, the tone or quality of the color required to cancel it is not affected by the change. (7) When the tone or quality of a color has been altered by the addition of a brightness excitation, the color component added can not be cancelled by mixing with the original color a color complementary to this component. Since, then, this fusion affects the positive and not the negative excitation and does not affect the cancelling action of the complementary colors, the conclusion is drawn that it takes place at some physiological level posterior to the seat of the after-image and contrast processes and to the cancelling action of the complementary colors. This study deals, however, only with the measure of the effect of the fusion of brightness and color as it occurs in central vision.

In order to extend the investigation to the peripheral retina, a third study was begun in June 1911. Its object was as follows. (1) It was planned to determine the effect of the fusion of brightness with color at a number of points from the center to the periphery of the retina, and to see how far the following points can be explained in terms of this action: (*a*) the influence upon the limits of color sensitivity of the brightness of the surrounding field and of the preëxposure; and (*b*) the color changes that occur in passing from central to peripheral vision. (2) A

comparative study was to have been made of the chromatic and achromatic phenomena of the peripheral retina. Both of these sets of phenomena for the peripheral retina show a number of striking differences from the phenomena of the central retina. Some of these points of difference are as follows: (*a*) There is considerable difference in the action of the achromatic qualities on color. (1) They inhibit or reduce the saturation of color much more strongly in the peripheral than in the central retina. (2) Of the achromatic qualities, white inhibits all colors the most strongly and black the least strongly in the central retina, while near the limits of sensitivity in the peripheral retina, black inhibits red and yellow the most strongly and white the least strongly. (3) The change in the tone or quality produced by adding white or black is much more pronounced in the peripheral retina and is often in a different direction. For example, black added to yellow in daylight illumination in the central retina turns it towards green; while in the peripheral retina the change is towards red. (*b*) Varying the brightness of the surrounding field has more effect on colors in the peripheral than in the central retina. (*c*) Exhaustion to color takes place more rapidly in the peripheral than in the central retina, that is, the change of saturation per unit of time is faster. (*d*) The colored after-image is of very short duration in the peripheral retina, but in proportion to its duration, it is much more saturated than the after-image of the central retina. (*e*) Some of the differences with regard to the achromatic phenomena are as follows. There is a very strongly increased sensitivity to contrast and to flicker; adaptation or exhaustion occurs very rapidly; the after-image is quickly aroused, is relatively very intensive, and in proportion to its intensity lasts a very short time; and so on. These points of difference raise the question how far we need go in assuming a different mechanism for the two parts of the retina. The purpose of our investigation was to have been primarily to determine how many of these differences are due at least in part to the difference in the state of brightness adaptation of the central and of the peripheral retina. (3) Maps were to have been made showing the sensitivity of the eye to the different

colors for three kinds of background (white, black, and gray of the brightness of the stimulus color). These three backgrounds were selected because they represent the extreme situations with regard to achromatic induction: maximal black induction, maximal white induction, and no induction; and, therefore, represent the best conditions that can be obtained for the study of the effect of the brightness of the surrounding field upon the local sensitivity of the retina. A sufficient number of meridians were to have been worked over to give an accurate outline of the zones of sensitivity for the three kinds of background used. Gradients were to have been established showing the falling off in sensitivity from the fovea outwards. Also the changes in color tone were to have been determined from point to point for all the backgrounds. Both sets of determinations were to have been made by matching in central vision what is seen in peripheral vision. The object of this investigation was to have been to give a complete representation of the sensitivity of the entire retina, quantitative and qualitative, in terms that are more or less familiar to all, namely, the sensation values of the central retina. It was found, however, that the large M. V. occurring in the work from observation to observation rendered the extended comparative investigation planned impossible. The original plan had, therefore, for the time to be abandoned, and the present study was undertaken.

This study aims (1) to determine what are the factors that influence the sensitivity of the retina to color; (2) to make a quantitative examination of the factors extraneous to the stimulus; and (3) to provide methods for their standardization. For the sake of historical continuity, the study is preceded by an historical and critical résumé of the analyses of factors influencing color sensitivity that have been made up to this time and of the attempts to standardize. It may be stated in passing that with the control of factors rendered possible by this study, the original plan of work has been resumed and in part completed. It will be published in the near future.

There remains to be mentioned the relation of the present study to the final one of the series. The latter has developed

from the historical and critical résumé mentioned above of the investigations that have been made to determine the factors that influence the sensitivity of the retina to color. In the course of this discussion various deficiencies have been pointed out in the methods used by previous investigators in their attempts to control these factors, and ways have been devised to correct these deficiencies. The factors that influence the sensitivity of the retina to color may be divided into two classes: those pertaining to the stimulus, and those extraneous to the stimulus. The experimental part of the present study is especially directed toward making a quantitative estimate of the latter set of factors under various typical conditions obtaining in the investigation of color sensitivity and toward securing effective methods of control. No concern is had, however, to standardize the factors pertaining to the stimulus any farther than is necessary to accomplish this purpose. The more effective standardization of these factors will form the subject of our future work. The question of intensity will be taken up first. It has been shown in the historical part of the present study that this factor has been most inadequately handled by previous investigators. In determining the comparative sensitivity of the retina to the different colors, for example, either no account has been taken of the different intensities of the colors used, or incorrect methods have been employed of equalizing these intensities. In no case has the determination been made in terms of units that can be compared. It is the writer's purpose to make an exhaustive determination of the sensitivity of the retina to the different colors in terms of such units. The comparative limits of sensitivity will be determined in a number of meridians with stimuli equalized in energy, and the limens and the j.n.d's. of sensitivity at different degrees of intensity will be determined in terms of radiometric units at various points from the center to the periphery of the retina in the different meridians. This investigation in fact is now in progress. A preliminary statement of the plan of this work has already been published by the writer in collaboration with Professor Ferree (American Journal of Psychology, 1912, XXIII, pp. 328-332).

From the above discussion of the place of the present study in the series, it will be evident to the reader how extensively this study has been due to the instruction, guidance, advice, and assistance of Professor Ferree, and how great a debt of gratitude the writer owes him. In stating his share and collaboration in the studies preceding and following this in the series, I can indicate perhaps more fully than in any other way the share he has had both directly and indirectly in the production of the present study.

I. INTRODUCTION.

In no branch of psychological optics does one find such varied and contradictory results as in the work on the color sensitivity of the peripheral retina. This is doubtless due in minor part to the intrinsic difficulty of the indirect vision observation, but in major part it is due to the lack of adequate standardization of the factors that influence the local stnsitivity of the peripheral retina. These factors may be divided into two classes: (*a*) those pertaining to the stimulus, or the source of light; and (*b*) those extraneous to the source of light. In the former class may be included the size, intensity, and brightness of the stimulus; in the latter, the preëxposure or what the eye has rested on before being exposed to the stimulus, the surrounding field, and the general illumination of the visual field.[1] The work of standardization thus far has been directed largely towards the factors in the former class. Of the factors in the latter class, attempts have been made, as will be shown later in the discussion, to standardize only the influence of surrounding field. The recognition of the importance of this factor came relatively late in the development of the technique of the subject. It was at one time thought that the use of the perimeter and the dark-room provided ideal conditions for testing the local sensitivity of the peripheral retina, because by this means the local area alone was stimulated by light, hence it was thought that the influence of the surrounding field was eliminated. We know now that these conditions were not so ideal as they seemed, that a dark- as well as a light-

[1] In case the colored light is obtained by reflection from a pigment surface, some exception may be taken to the above classification, for unless some especial device be used to illuminate the pigment surface, the intensity of the stimulus will depend upon the degree of the general illumination of the visual field, and the brightness of the stimulus will also, to a certain extent, be dependent upon the general illumination. In such a case, these factors would have to be included in both classes. If on the other hand the colored light is obtained by means of standard filters, or from the spectrum, the illumination of the visual field will exercise its influence entirely independently of any effect on the stimulus.

adapted retina influences by contrast the sensitivity of the area stimulated. The use of the perimeter and dark-room accomplishes, then, but a very small part of the purpose for which it was intended. Instead of eliminating altogether the influence of the brightness of the surrounding field, it makes only one phase of it constant. It standardizes by giving us one state of brightness-adaptation alone, namely, the adaptation of the dark-room.[2] The campimeter was devised especially to correct this deficiency. Its purpose is to control and standardize the influence of the brightness of the surrounding field when one is working with a light-adapted retina. But the campimeter, like the perimeter, has accomplished only in part the purpose for which it was intended. It standardizes the influence of the surrounding field for one degree of illumination only, because the influence of the campimeter screen changes markedly with changes in the illumination of the visual field. There are two reasons for this. (*a*) A brightness match between the colored stimulus and the gray of the surrounding field made at one illumination will not hold at another. And (*b*) the sensitivity of the retina to brightness induction changes markedly with changes in the general illumination. This latter point is especially true in the peripheral retina where changes which are too small to be detectable by any current photometric device produce quite a noticeable change in the amount of induction between two surfaces of different brightness. The campimeter, then, is almost useless as an instrument of precision, unless the general illumination can be rendered constant or some means can be devised for standardizing the observation for changes of illumination. No satisfactory method has as yet been obtained for keeping the illumination of a room by daylight constant. To keep it constant presupposes what has not as yet been provided, namely, a sensitive means of measurement. Constancy may be approximated by artificial illumination,

[2] As will be shown later in the paper, neither the influence of surrounding field nor of preëxposure can be eliminated when the observation is made in the dark-room. The influence of these two factors can be eliminated only by working in a light-room of constant intensity of illumination, and by using a preëxposure and a surrounding field of the brightness of the color used for the stimulus.

but no artificial source has yet been devised which gives a light that approaches average daylight[3] sufficiently closely in composition to warrant its use in color work. Of the various sources of light the Moore Tube comes nearest to doing this, but spectrophotometric and colorimetric determinations show that the light from it contains an excess of blue[4] and, therefore, although it has been adopted by various textile concerns for use in color matching, its substitution for daylight can scarcely be recommended for the more exact requirements of color optics. Ives and Luckiesh[5] attack the problem of producing artificial daylight from another side. By their subtraction method they claim to have gotten the closest approximation to average daylight yet attained. They aim to cut out by absorbing screens the excess of red and yellow in artificial light due to the comparatively low temperature of artificial illuminants. Tungsten lamps are used by them as the source of light, and two kinds of commercial glass approximating in their absorptive action cobalt blue and signal green are used as screens. In order to correct for the pronounced band of yellow-green transmitted by the cobalt blue, a film of gelatine dyed with rozazeine is also used. Although according to comparative measurements made by Ives and Luckiesh the light thus gotten is the closest approximation to average daylight yet obtained, still it shows a deficiency of 15% in the green and about 25% in the blue. Moreover, the spectrum of this light does not show the brightness distribution of the spectrum of daylight. Since the absorbing screens cut down the light emitted by the tungsten lamp to 15% of its original intensity, the spectrum of

[3] For results of measurements of the color values of average daylight, see Nichols, E. L. *Transactions of the Illuminating Engineering Society*, 1908, III, p. 301. Ives, H. E. The Daylight Efficiency of Artificial Illuminants. *Transactions of the Illuminating Engineering Society*, 1909, IV, pp. 434-442; Color Measurements of Illuminants. *Transactions of the Illuminating Engineering Society*, 1910, V, pp. 189-207.

[4] See Ives, H. E. Color Measurements of Illuminants. *Transactions of the Illuminating Engineering Society*, 1910, V, p. 206; and Rosa, E. B., quoted by Moore, D. McF. A Standard for Color Values. *Transactions of the Illuminating Engineering Society*, 1910, IV, p. 224.

[5] Ives, H. E. and Luckiesh, M. Subtractive Production of Artificial Daylight. *Electrical World*, 1911, LVII., pp. 1092-1094.

the light finally given out shows the brightness distribution characteristic of lights of low intensity, unless the original light-source is of extremely high candle-power.

We seem thus compelled either to give up the investigation of the sensitivity of the retina for daylight illumination, or to devise some means of keeping this illumination constant. At an early stage in the study of the color phenomena of the peripheral retina begun four years ago and still in progress in the Bryn Mawr Laboratory, the writer was compelled to take into account the influence of the changes in the illumination of the visual field upon the color observation. The changes of illumination that took place from day to day, the progressive changes during the day, and the many sudden changes even in the course of an hour, rendered any constancy, or close reproduction of results entirely out of the question. The consideration of this factor led in turn to a general study of the conditions that influence the color observation. It is the purpose of this paper to report the results of that study. The report will take the following form.

(1) A résumé and criticism will be given of previous studies of factors, and of attempts to standardize. (2) The color observation will be reexamined for the factors that influence its results, and a study of these factors will be made with the following points in view: (*a*) Their influence will be measured under various typical conditions obtaining in the work on color sensitivity. (*b*) Their effect on the limen of color at different points in the retina and on the limits of color sensitivity will be determined. (*c*) An explanation based on the conclusions drawn from (*a*) and (*b*) will be made of the results of other experimenters and of the contradictions found in these results. (3) From this study of the influence of the factors, it will be determined what factors need to be standardized in the various kinds of work on color sensitivity and methods will be devised for their standardization.

In the latter part of the work especial attention will be given to the effect of general illumination and of local preëxposure. The writer finds these to be the two most important factors extraneous to the source of light that influence the results of the color obser-

vation, and yet, so far as she is able to determine, up to this time no attempt worthy of more than passing consideration has been made to standardize either factor in investigations of color sensitivity. In fact, it can scarcely be said that either has been included in the list of factors by any previous writer. The effect of the general illumination has received only casual mention by Ole Bull and a few others, and the brightness of the preëxposure has not been clearly recognized as exerting any influence whatever.

II. HISTORICAL AND CRITICAL.

A. FACTORS THAT HAVE BEEN FOUND TO INFLUENCE THE SENSITIVITY OF THE RETINA TO COLOR.

1. *Size of the Stimulus.*

An increase in the size of the stimulus is generally considered to be equivalent in some proportion to an increase in intensity.[1] It is but natural, then, to think that an increase in the size of the stimulus would both lower the limen of sensitivity and extend the limit of the zone within which a given color can be sensed. The question with regard to the limits of sensitivity is, however, not so simple as it seems. In the first place, the limit of the zone may not be extended, because the retinal sensitivity may fall off so rapidly at the point worked upon, that the increase of stimulation is not sufficient to overweigh the loss. In the second place, the effect of the increase of area may depend to some extent upon the area of the original stimulus. For example, fatigue is set up so easily with very small stimuli that an increase up to a certain point is advantageous, while, on the other hand, the outer margin of large stimuli may extend so far into the zone of relative insensitivity that a further increase of area becomes ineffective. In the third place, the effect may vary with the meridian of the retina investigated. Two reasons may be assigned for this variation. (*a*) We should expect the effect to be in some measure proportional to the rapidity with which the retina falls off in sensitivity from the fovea to the periphery. For example, in the temporal and lower

[1] Raehlmann, E. Ueber Farbenempfindung in den peripherischen Netzhautpartien in Bezug auf normale und pathologische Brechungszustände. Inaug. Diss., Halle, 1872.

While the work of Raehlmann and others shows in general the truth of the above statement, no systematic determination of the exact relation of change of area to change of intensity has yet been made. This determination for the sensations aroused both by white and colored light is now in progress in the Bryn Mawr laboratory.

meridians, where the sensitivity falls off sharply, we should expect little if any effect; while in the nasal and upper regions, where the decrease is much more gradual, we should expect considerable effect. (*b*) In the nasal and upper meridians, the limits of sensitivity extend much farther toward the periphery than in the temporal and lower meridians. There is in these meridians, then, as the limits of sensitivity are approached, a relatively greater shrinkage in one dimension of the stimulus, owing to the greater angle of excentricity, than occurs in the temporal and lower regions. In proportion as this shrinkage causes a shortening of one dimension of the stimulus, it adds to the range of areas over which an increase is of advantage for extending the limit of sensitivity.

A survey of the literature on peripheral vision shows that the size of the stimulus was early recognized as one of the factors influencing the sensitivity of the peripheral retina. In fact, the first investigation of peripheral sensitivity was made to determine the effect of the size of the stimulus. This work done by Hueck[2] in 1840, may be considered as pioneer, for although Troxler[3] and Purkinje[4] had previously mentioned the phenomena of peripheral vision, they had made no systematic attempt to investigate these phenomena. Hueck's object was primarily to study the effect of increase in the size of the stimulus upon the limits of the field of vision. Using gray paper stimuli of very small area, he observed the effect on the limit of vision (*a*) when their objective size was increased, and (*b*) when their apparent size was altered by a decrease in their distance from the observer, that is, by enlargement of the visual angle. He found that an increase in size produced in either of these ways caused a widening of the field of vision for that quality of stimulus. The investigation was also extended to color. Pig-

[2] Hueck, A. Von den Grenzen des Sehensvermögens. Müller's Archiv, 1840, p. 95.

[3] Troxler, D. Ueber das Verschwinden gegebener Gegenstände innerhalb unseres Gesichtskreises. Ophthal. Bibliothek herausgegeben von Himly u. Schmidt, Jena, 1804, I, 2. pp. 1-53.

[4] Purkinje, J. Beiträge zur Kenntniss des Sehens. 1823, I, p. 76; 1825, II, p. 14.

ment papers were used. This investigation showed that the limits of color sensitivity also are influenced by the size of the stimulus. An interesting table was compiled which shows that by altering either the size of the stimulus or the visual angle it subtends, the limit of sensitivity can be made to vary by amounts equal to 1° over a wide range of the retina. Hueck's conclusion, that the limits of color vision are influenced by the size of stimulus, was confirmed by Aubert[5] in 1865. Five years later it was contradicted by Woinow.[6] Woinow worked in the dark-room, using for stimuli colored glasses illuminated by a shaft of sunlight of variable extent. He claimed that "die Grenze immer dieselbe ist, ohne Rücksicht auf die Grösse der Pigmentfläche, wenn die Gesichtswinkel nicht von der Mitte sondern von dem dem Auge zugekehrten Rande der Pigmentfläche berechnet werden." No information is given as to the size of stimuli employed. Krükow,[7] repeating Woinow's precaution of measuring the angular distance to the inner edge of the stimulus rather than to the middle, confirmed the conclusion that the boundaries of the color zones are absolute, within certain limits of size of stimulus. His stimuli were 3, 6, and 9 mm. square. Aubert[8] in 1876, repeated the observations recorded in his earlier work. Colored squares with sides varying from 1 mm. to 32 mm. placed at a distance of 20 cm. from the eye were used as stimuli. The results he obtained led him to believe that the size of the stimulus is a factor in determining the limits of sensitivity. He writes: "Die Grösse des farbigen Objectes massgebend ist für die Entfernung vom Centrum, in welcher es noch farbig empfunden wird. Die gegentheilige Behauptung Woinow's . . . muss ich nach vielfacher, wiederholter Untersuchung für falsch erklären." He mentions the precaution used by Woinow as to the measurement of the angular distance, but does not definitely state that he himself took this precaution. Raehl-

[5] Aubert, H. Physiologie der Netzhaut. Breslau, 1865, p. 121.

[6] Woinow, M. Zur Farbenempfindung. A. f. O., 1870, XVI, p. 219.

[7] Krükow. Objective Farbenempfindung auf den peripherischen Theilen der Nezhaut. A. f. O., 1874, XX,,, pp. 255-296.

[8] Aubert, H. Physiologische Optik. Leipzig, 1876, pp. 541-544.

mann,[9] Schön,[10] Schirmer,[11] and Briesewitz,[12] all agree with Aubert; but they also have not mentioned their method of measurement.

In Tschermak,[13] however, we find an investigator who has observed Woinow's precaution and yet has obtained results that are contradictory to Woinow's. He investigated the factors which condition the colorless vision of the peripheral retina, and showed that neither the red-green nor the totally color-blind zones of the normal retina are invariable in extent. Size of stimulus was found by him to be one of the factors that determine the breadth of these zones. This he demonstrated on the Hering apparatus for investigating the color sensitivity of the peripheral retina, an apparatus consisting of a campimeter screen with an opening behind which the stimulus is placed. Tschermak's screen was of gray paper. The size of the stimulus-opening was regulated by means of two gray slides which widened the opening either on the side within the visual field and toward the fovea, or on the other side toward the periphery. Using a small stimulus-opening, he determined the degree of excentricity at which *Urgrün* and *Urroth* appeared colorless. He then widened the stimulus-opening toward the fovea and found that the color was sensed. No conclusion, however, can be drawn from this because he had extended the inner margin of the stimulus into the region sensitive to color, hence the sensation aroused may have been due to that cause rather than to the increase made in the area of the stimulus. He next widened the original stimulus-opening toward the periphery. This caused an increase in the area of the retina stimulated, without extending the margin of the stimulus into the field sensitive to color. Since in this case also the color was sensed, Tschermak concludes that the

[9] Raehlmann, E. loc. cit.

[10] Schön, W. Ueber die Grenzen der Farbenempfindung in pathologischen Fällen. Klinische Monatsblätter, 1873, p. 171.

[11] Schirmer, R. Ueber erworbene and angeborene Anomalien des Farbensinns. A. f. O., 1873, XIX, p. 194.

[12] Briesewitz. Ueber das Farbensehen bei normalem and atropishem Nervus Opticus. Inaug. Diss., Greifswald, 1873.

[13] Tschermak, A. Beobachtungen über die relative Farbenblindheit in indirectem Sehen. Pflüger's Archiv, 1890, LXXXII, pp. 559-560.

limits of color sensitivity are influenced by the area of the stimulus. It is in the second method of increasing the area of the stimulus that Tschermak took the precaution mentioned by Woinow relative to the measurement of the angle of excentricity.

But it is obvious that the method of measurement need not have been the only cause of variable results in work of this kind. The meridian tested may have been, as we have already suggested, a second cause. That certain regions of the retina react differently to an increase in the area of the stimulus, is noted in a brief paragraph by Kirschmann.[14] Using stimuli of 28, 40, and 58 mm. in diameter, he found that the color sensitivity of the peripheral retina is dependent to different degrees in different meridians upon the size of the stimulus. In the lower and temporal meridians, the zone sensitive to each color was widened very slightly by increasing the area of the stimulus, and never beyond certain limits. On the upper and nasal parts of the retina, however, the possibility of widening the zones by this means seemed to be, he says, unlimited. Now we know that Woinow and Krükow obtained their results on the temporal meridian. Tschermak, however, does not state what region he investigated. If he worked in the nasal region, his conclusions may be reconciled with those of Woinow in the light of Kirschmann's work. These variations in the effect of area in different regions of the retina are no doubt due largely to the difference in the rapidity with which sensitivity falls off from the center to the periphery of the retina along the several meridians. Where the decrease is gradual, as is the case in meridians that have wide limits of sensitivity, more effect might be expected than where the sensitivity decreases rapidly.

A third cause of the variable results recorded may have been the range of size of stimuli employed. The retina fatigues easily to very small stimuli; hence an increase in size up to a certain point is advantageous. On the other hand, the margins of very large stimuli may extend so far into the zone of insensitivity that a further increase is ineffective. Krükow no doubt

[14] Kirschmann. A. Die Farbenempfindung bei indirectem Sehen. Philos. Studien, 1893, VIII, p. 612, 613.

referred to this fact when he said that color sensation is independent of the size of the stimulus, but only within certain limits. An interesting conclusion reached by Abney[15] may also be mentioned in this connection. He wished to determine at what intensity the different colored spectral lights were brought below the limen of sensation both in central and at various points in peripheral vision. He found, however, that the intensity of the stimulus is not the only factor to be considered. A stimulus 2 inches in diameter, for example, was seen at a lesser intensity than a stimulus ½ inch in diameter. He further found that it is not the area, but the shortest dimension of the stimulus, vertical or horizontal, which determines the intensity required to render the stimulus subliminal.

The following table has been compiled from the results of his work in central vision.

Stimulus		*Relative Intensity*	*Value of Light*
disc	.95 in. diameter	234	97.4
square	.84 in. x .84 in.	216	139.2
rectangle	1.68 in. x .42	152	495.2
square	.84 in. x .42	154	478.4

The areas of the disc, the square, and the first rectangle are equal, but the rectangle which has the shortest dimension, requires 400 units more of light intensity than does the disc in order to be made just subliminal. The fourth stimulus has half the area of the third, but their shortest dimensions are equal, and accordingly the same amount of light is required to render them both just subliminal. The experiments were extended by Abney to the peripheral retina, and the conclusion was again reached that the shortest dimension of the stimulus and not its area determines the reduction in intensity necessary to render the stimulus just subliminal (p. 183). Since Abney found further that "there is a simple connection [relation] between the intensity of the stimulus color and the extent of the color field," we may infer that he would have us conclude that the extent of the color field is also influenced by the shortest dimension of the stimulus.

The present status of this point may be summarized as follows:

[15] Abney W. de W. The Sensitiveness of the Retina to Light and Colour. Philos. Trans., 1897, CXC, Ser. A, pp. 169-171.

Within a certain range of dimensions and particularly for certain regions of the retina, the size of the stimulus is an important factor in determining the extent of the color zones. And with regard to size, the shortest dimension of the stimulus and not its area is, according to Abney, the determining factor. Care must be taken, therefore, to measure accurately the size of the stimulus used in peripheral investigation, also its distance from the observer, and to keep these measurements uniform throughout the investigation.

2. *Intensity and Brightness or White-Value of the Stimulus.*

(*a*) *The confusion that has arisen with regard to the meaning of intensity and of brightness, and its effect upon the development of methods of working.*

Before we attempt to discuss the influence of the intensity and the brightness of the stimulus upon the limits of color sensitivity, some attention should be given to a definition of terms. The need for this will be shown by a brief examination of the literature on these subjects. A great deal of confusion as to terminology seems to exist, and not a little misinterpretation of fact seems traceable to this confusion. The greater part of the confusion arises from the use of the word *intensity*. This term has been employed at various times to indicate (*a*) the energy of a beam of spectral light homogeneous as to color; (*b*) the white-value of a color; (*c*) the saturation of a color; and (*d*) the energy of light-waves reflected from a pigment surface as conditioned by the general illumination of the visual field. This equivocal use of the term has now and then apparently led to a wrong interpretation of results, and this in turn to the modification of experimental technique. An example of this is found in the work done by Baird in the Cornell laboratory on *"The Color Sensitivity of the Peripheral Retina."*[16] In his review of the literature, Baird finds data that lead him to assume that an equation of the white-values of the stimuli employed is essential for a determination of the relative extent of the retina's sensitivity to the different colors. Apparently these data are derived

[16] Baird, J. W. The Color Sensitivity of the Peripheral Retina. Carnegie Institution of Washington, 1905.

mainly from three sources: (*a*) from a study of the color sensitivity of the peripheral retina made by Aubert; (*b*) from a study by Abney of the effect of changes in the energy or intensity of spectral light upon sensation; and (*c*) from a study of the limits of color sensitivity made by Landolt.[17] An examination of the investigations made by these men shows, however, that Baird's conclusion is apparently based upon a loose construction put upon the meaning of certain terms. The most striking example of this, as we shall see, results from the interpretation given by Baird to the term *intensity*. Baird uses *intensity* to indicate *luminosity* and, as we shall show, he also uses *luminosity* interchangeably with *brightness* or *white-value*. Landolt and Abney, on the other hand, from the results of whose investigations of the effect of intensity on color sensitivity Baird largely draws his conclusions as to the need of equating the white-value of his stimuli, clearly use the term *intensity* to mean the *energy* of the light-waves coming to the eye.

According to Baird, the first mention of the need to equate in brightness was made by Aubert. Baird writes: "His [Aubert's] results may be summarized as follows:

"1. The brightness of the background has a most pronounced influence upon the extension both of the color sensitivity and of the brightness sensitivity.

"2. The extension of the color zones increases with increase of area of stimulus.

"3. The color sensitivity decreases at very different rates upon different retinal meridians.

[17] Baird claims to derive authority also from the work of Raehlmann, Klug, Chodin, Bull, Hess, and Hegg. We have considered that this authority is derived mainly from Aubert, Landolt, and Abney, however, because Baird discusses the results of these three men and to some extent their methods of working, giving several sentences to show that their work points out the need for equation of the white-values of the stimuli employed to investigate color limits. To the other men from whom he claims to derive authority, Baird devotes merely a sentence to each which states, in case of Raehlmann and Klug, that they had found that the color limits vary with changing brightness of stimulus; in case of Chodin, that he believed that brightness equation was necessary; in case of Bull, Hess, and Hegg, that they had equated the white-values of their stimuli. The discussion of these cases will be taken up later in the paper (see pp. 51-53).

"4. The transitions of color tone are as follows: Red passes through reddish-yellow and yellowish-gray to gray; green becomes yellowish, while yellow and blue undergo no change of tone, but decrease in saturation and finally appear gray.

"5. The relative extension of the color zones can not be determined with any degree of accuracy. Since the width of the color zone is a function of the luminosity of the stimulus, the color-stimuli employed in the determination of comparative retinal limits must all be equated in brightness.

"6. There is a close analogy between the functioning of the central and peripheral parts of the retina."[18]

Baird seems to derive his authority for the need to equate in brightness, so far as Aubert is concerned, from the fifth of these points of summary. From the wording of the text it is impossible to state the exact source of Baird's quotation since he bears himself out in his summary only by a general reference to a long list of Aubert's articles on vision.

But the organization of this summary is so closely akin to that given in the *Physiologische Optik*,—the only difference being in the omission by Baird of the third item in the *Optik* summary,—that one seems justified in asserting that this work contains the source of the statement quoted above. In no other of Aubert's articles are all of the points mentioned by Baird touched upon. The earlier articles are narrower in scope than the *Optik* and treat of fewer factors.

Aubert's statement of results in the *Physiologische Optik* is as follows: "Durch meine Versuche wurde festgestellt

"1. der grosse Einfluss welchen die Umgebung der Pigmente auf die Farbenempfindung auch beim indirecten Sehen hat.

"2. der Umstand, dass die Grösse des farbigen Objectes massgebend ist für die Entfernung vom Centrum, in welcher es noch farbig empfunden wird.

"3. dass Pigmente verschiedener Farbentöne unter sonst gleichen Umständen verschiedene Grenzzonen für die Erkennbarkeit der Farbe zeigen.

"4. dass in die verschiedenen Meridianen der Netzhaut die

[18] Baird, J. op. cit., pp. 12-13.

Grenzzonen für die Farben sehr verschieden weit von dem Fixationspunkte liegen.

"5. Schon Purkinje hat verschiedene Uebergänge durch Farbentöne und Farbennuäncen beobachtet, und zwar geht auf schwarzem Grunde nach Aubert: Roth durch Rothgelb und Gelbgrau zu Grau, Blau durch immer weisslichere Nuäncen zu Grau, Grün durch Graugelb zu Grau, Gelb durch Graugelb zu Grau.

"6. Donders und Landolt haben nachgewiesen, dass die Farbenempfindung auf den peripherischen Netzhautzonen eine dem Centrum gleiche bleibt, wenn die Intensität der Beleuchtung gesteigert wird: also auch beim indirecten Sehen sind Gesichtswinkel und Helligkeit massgebend für die Farbenperception.

"7. dass die peripherischen Theile der Netzhaut für die Farbenempfindung viel schneller ermüden, also die centralen."[19]

To Baird's fifth point of summary, the closest approximation that the writer is able to find anywhere in Aubert's works is the sixth conclusion quoted above from the *Optik*. This is: "Donders and Landolt haben nachgewiesen, dass die Farbenempfindung auf die peripherischen Netzhautzonen eine dem Centrum gleiche bleibt, wenn die Intensität der Beleuchtung gesteigert wird: also auch beim indirecten Sehen sind Gesichtswinkel und *Helligkeit massgebend für die Farbenperception.* Nagel bestätigt Landolt's Angabe."[20] The question here is whether *Helligkeit* in the above quotation means *brightness of stimulus* which, if our assumption with regard to the source of his authority is correct, Baird has apparently interpreted it to mean. The following points may be cited to show that such an interpretation is very strongly open to question. (*a*) Aubert himself does not use *Helligkeit* in connection with a qualifying phrase, for example, *Helligkeit der Farben* or its equivalent, while so far as the writer is able to determine, he never uses *Helligkeit* as referring to the *brightness of color* without the qualifying phrase. For example, in his Physiologische Optik p. 527 he uses Helligkeit der Farben; p. 528, Helligkeiten der verschiedenen Abtheilungen des Spectrums; p. 529, Helligkeiten der Farbentöne des Sonnenspectrums;

[19] Aubert, H. Physiologische Optik, Leipzig, 1876, pp. 541-545.
[20] Aubert, H. Physiologische Optik, Leipzig, 1876, p. 545.

same page, Helligkeiten der Farben; p. 530, Helligkeiten der Abtheilungen des Spectrums. In his Physiologie der Netzhaut p. 109 he uses, Helligkeit der Pigmente. The same expression is used again on pp. 111 and 112. (*b*) When using *Helligkeit* without a qualifying phrase, Aubert commonly refers to the *intensity* or *brightness of the general illumination.* For examples of this usage, see Physiologie der Netzhaut, pp. 109, 110, 124; Physiologische Optik, p. 532, and other places. (*c*) No evidence can be obtained from Landolt from whom the citation is made that brightness of color is referred to. In fact the evidence is strongly against this interpretation. As will be shown in detail (pp. 24-25), Landolt worked with colors of varying energy. He used as stimuli very intense spectral light and pigment papers. The energy of the former was varied directly, of the latter by changing the general illumination which altered the amount of colored light reflected to the eye. In the general statement of his problem Landolt is not concerned with the effect of the brightness of his colors; nor are his results couched in terms of the effect of the brightness of colors. His sole interest was to find the effect on sensation of using colors of great energy or intensity. In the above quotation from Aubert, then, we may conclude that it is strongly open to question whether *Helligkeit* is not also used here in the sense in which we have shown that Aubert most frequently uses the term: the brightness of the general illumination (see (*b*) above). If so, what he really does claim in this statement, therefore, is that when one is working with pigment colors, the degree or brightness of the general illumination with all of its influences, namely, its effect on the intensity of color, on the brightness of color, on the brightness of the surrounding field, the preëxposure, etc., is one of the factors that determine the extent of the color field; not simply one of these influences, the brightness of color, as he is interpreted to claim by Baird.[21] Moreover, the writer is compelled to say that in a careful reading of all the articles by Aubert contained

[21] For Aubert's own statement of his opinion on the question of the influence upon color sensitivity exerted by the brightness of the stimulus see this article, pp. 40-44.

in the long list to which Baird refers, she is unable to find a single statement that would justify the conclusion that Baird has drawn in his fifth point of summary.

Towards Landolt and Abney, Baird takes a slightly different attitude. He does not hold that they have mentioned a need to equate in brightness. In their results, however, he finds justification for equating the white-values of his own stimuli from the construction he puts upon their use of the words *luminosity* and *intensity*. Abney,[22] a physicist, had defined *luminosity* as equivalent to *intensity*. In his experiments he had increased or diminished the luminosity or, as he also says, the intensity of a beam of light by interposing in its path a wedge graduated in thickness. The wedge was made of gelatine in which were scattered black opaque particles. The energy of the beam of light was diminished by amounts depending on the thickness of that part of the wedge through which it was made to pass. This "obstruction method" resulted not only in a decrease of the energy of the light, but in a darkening of the stimulus. But Abney was not at all concerned with the effect of the lightness or darkness aspect of the stimulus:—in other words, with the relative inhibitive action of white and black and its influence on the limits of color sensitivity. His purpose was to vary the energy of the light-waves coming to the eye by "obstructing" them by known amounts, and to ascertain the effect of this change upon the color limits. It is true that the lightness or darkness of the sensation quality was altered incidentally, but he apparently had no thought of saying that this was in any sense responsible for the effect obtained, nor is it a necessary inference from his work. Hence Baird is not justified in stating (p. 31) that Abney makes the brightness of the stimulus a factor in determining the color limit, if we take our clue as to what Baird means by brightness from the following passage. "No determination of the relative extensions of the various color zones can ever yield comparative results unless it be accomplished by means of stimuli of equal brightness, or, more correctly speaking, of equal white-value" (see p. 37). For Abney assuredly, does not mean by *lum-*

[22] Abney, W. op. cit., 155-195.

inosity what Baird calls ***brightness*** or ***white-value***. Baird falls into a similar error in his treatment of Landolt's results. He says: "An important feature of Landolt's paper is his insistence that no investigation of color vision is complete unless it takes into account the relative luminosity of the stimuli employed" (p. 17). Now when we read in a footnote (see Baird p. 34) that "Under brightness [of stimulus] is included both absolute and relative luminosity of stimulus, *i.e.*, its own brightness and its brightness contrast with its background," we see that the relative luminosity referred to by Landolt means for Baird relative brightness or white-value, and that the work of Landolt is brought forward as as evidence for the necessity of equating the white values of the stimuli. Now Landolt worked with both spectral and pigment stimuli. In case of the first, his method was to increase the energy of spectral light; and in case of the second, to increase the amount of light coming to the eye from a pigment surface by increasing the general illumination of the room. Here, as in the case of Abney, we have a change in the amount or energy of the colored light coming to the eye, and incidentally a change in the white-value of the sensation aroused. No separation is made, however, of the two factors: (*a*) the altered energy of the colored light, and (*b*) the change in the white-value of the sensation aroused. Yet Baird finds reason to conclude from Landolt's results that the white-value of the color influences the limits of sensitivity. It is obvious that Landolt's results do not show this at all. All that they do show is that when the amount of colored light given to the eye is increased or decreased, the extent of the zones of sensitivity is altered.[23]

Whether or not the white-value of the stimulus can be considered to any degree responsible for changes in the color limits

[23] These three cases taken from Baird's discussion of the work of Aubert, Abney, and Landolt are examples of the cases referred to earlier in the chapter in which a confusion as to terminology has led to a wrong interpretation of results which in turn has been the cause of changes in technique. Baird was led by this confusion, in part intrinsic and in part due to his own misinterpretations, to think that these three men considered that the white-value of the colored stimulus affects the extent of the retina's sensitivity to it, and was influenced thereby to equate the white-values of his stimuli without further investigation.

will be considered by the writer in the experimental section of this paper. What we wish to point out here is that without the isolation and the separate investigation of this factor, Baird concludes from the work of previous investigators in which intensity or energy changes have been made in the stimulus, that the white-value of the stimulus influences the boundaries of the color zones and that, therefore, stimuli should be equated in white-value in all work on the limits of color sensitivity. He says: "It has been been established in hosts of instances[24] that change of luminosity is, within limits, invariably attended by a corresponding change in the extension of the retinal zone within which the color of the stimulus is recognized. Its significance for the problem is self-evident. No determination of the relative extension of the various color zones can ever yield really comparative results unless it be accomplished by means of stimuli of equal brighness, or, speaking more correctly, of equal white-value" (p. 37). While we grant the significance of changes of luminosity or intensity in the sense in which Abney and Landolt use the terms, we do not admit that this aspect of the stimulus can be standarized in terms of white-value; nor do we grant that any definite evidence whatsoever can be gathered from the results we have quoted above, to show that changes in the white-value of a stimulus affect the limits of the retina's sensitivity to its color, provided the amount of colored light coming to the eye remains unaltered.

To sum up: (*a*) The white-value of a stimulus may be varied without altering the amount of colored light coming to the eye. This factor, then, may be isolated and its effect on the limits of sensitivity determined apart from any change in the physical intensity of the stimulus. (*b*) Unless this separation is made, we have no right to conclude that the white-value of the stimulus affects the limits of sensitivity. Baird, for example, drew this conclusion from work in which the separation was not made. (*c*) The confusion that exists with regard to color terminology

[24] Beside the three instances mentioned here, Baird cites in support of his position the work of Raehlmann, Chodin, Klug, Bull, Hess, and Hegg. How far their work can justly be cited in support of his position will be shown on pp. 51-53.

has been, we believe, in no small measure responsible for Baird's conclusion.

The terminology which we propose to use in this report may be outlined as follows: *Intensity of stimulus* will be used to indicate the energy of light-waves coming to the eye. *Intensity of sensation,* or *apparent intensity,* will be used as its correlative subjective term. So used, it will signify merely energy or voluminousness of sensation and will have no reference whatever to the white-value of a color. *Saturation of the stimulus* will be used to indicate the proportion of colored to colorless light coming to the eye. *Saturation of color* or *saturation of the sensation* will be used as its correlative term and will refer to the proportion of chromatic to achromatic quality in the sensation. The achromatic sensations will be designated by the terms *white, black,* and *gray;* and the terms *brightness* and *white-value* will be used interchangeably to indicate the lightness or darkness of a color.

(*b*) *The effect of intensity of stimulus.*

A dependence of color sensation upon the intensity of the stimulus has been recognized since the observations of Purkinje. Purkinje noted also that a color stimulus gave a less intense sensation in the peripheral retina than in the central retina. Since that time, it has been claimed (*a*) that with stimuli of minimal intensity, no color sensation is aroused; (*b*) that the light-waves arousing the different monochromatic sensations must be of different intensities to give liminal color sensations; that is, the eye is not equally sensitive to waves of different lengths; (*c*) that, progressively, greater intensity of stimulus is required to give sensation as the stimulus is moved from the fovea to the periphery; (*d*) that the extent of the color fields is determined within certain limits by the intensity of the stimulus.

The influence of changes in the intensity of the stimulus upon the sensation of color has been investigated by three methods: (1) by determining the effect upon the limens of sensitivity; (2) by determining the effect upon the j.n.d. of sensitivity; (3) by determining the effect upon the limits of sensitivity.

The effect upon the limens of sensitivity. When working by this method, the investigator started with a stimulus that was

below the threshold of sensitivity, and increased its intensity until the sensation of color was just noticeable. This increase in intensity was accomplished in three ways: (*a*) by increasing the illumination of a pigment surface, and consequently the amount of colored light reflected to the eye; (*b*) by increasing the intensity of the light used to give a spectrum; (*c*) by increasing the proportion of color in a mixture of colored and gray pigment stimuli.

The first method of increasing the intensity of the stimulus was used in central vision by Purkinje[25] and Aubert.[26] Purkinje observed a representation of the spectrum in pigment colors while daylight advanced. He found that blue was the first color to be seen in its true color tone, green next, yellow next, and red last. He made no measurements, however, of the amount of light required to give a just noticeable sensation. Aubert illuminated a pigment surface 10 mm. square by daylight admitted into a dark-room through an adjustable opening in a window. He found that with an opening ¼, ½, or 1 cm. square, no sensation of color was obtained. His results are given in the following table.

Opening in window	*Stimulus*	*Sensation*
¼-½-1 cm^2	all	no color
1¼-1½	orange	red
2	O,Y,R, rose	O,Y,R, rose
3	blue	blue
3	light green	brown
3½	light green	light green
5	green	blue
8	green	green

Aubert found that the eye was most sensitive in order to orange, red and yellow, blue, and least sensitive to green.

The second method was used by Raehlmann and Butz. They both used the Bunsen spectroscopic apparatus, which provides for changes in the intensity of the stimulus by means of the Nichol's prism. Raehlmann[27] determined the limens of sensitivity to the

[25] Purkinje, J. op. cit., 1825, II, p. 109.

[26] Aubert, H. Untersuchungen über die Sinnesthätigkeit der Netzhaut. Pogg. Annal., 1862, CXV, pp. 87-116.

[27] Raehlmann, E. Ueber Schwellenwerte der verschiedenen Spectralfarben an verschiedenen Stellen der Netzhaut. A. f. O., 1874, XX,, pp. 232-254.

different spectral colors at the center of the retina, and at 30° and 60° in the horizontal nasal meridian. He found that the center was most sensitive in order to green, yellow, blue, violet, and red; and the periphery to yellow, blue, green, violet, and red. Butz's[28] procedure was as follows: He first determined the liminal value for each of his colors at the center. Starting with this value as unit, he determined how much this value had to be altered to give liminal sensation at 30° and at 60° in the horizontal nasal meridian. He found (*a*) that the sensitivity to each color increases from 0° to 30° and decreases from 30° to 60°; (*b*) that the amount of increase in sensitivity from 0° to 30° and the amount of decrease from 30° to 60° is different for the different colors, that is, the ratio of liminal sensitivity to any two colors is not the same from center to periphery; and (*c*) that the amount of the increase is greatest, and of the decrease is less in order for violet, yellow, blue, green, and red.

The third method was used by Aubert and Chodin, both of whom employed the Masson disc to find the limen of color sensitivity. Aubert[29] found that at the fovea, the eye is more sensitive to orange and yellow than to red and blue.. Chodin[30] found the sensitivity in the central retina to be greatest in order for orange, yellow, green, and least for blue. In the periphery, he found that the retina is more sensitive to blue and yellow than to red and green.

(*2*) *The effect upon the j. n. d. of sensitivity.* The effect of intensity upon the j. n. d. of sensitivity has been investigated by Lamansky and Dobrowolsky. Lamansky[31] used polarized spectral light, and worked in central vision. He found (*a*) that the j. n. d. of intensity for the different colors increases or, in other words, the sensitivity decreases, as the intensity of the stimulus is

[28] Butz, R. Vorläufige Mittheilungen über Untersuchungen der physiologischen Functionen der Peripherie der Netzhaut. Archiv für Anatomie und Physiologie, 1881, pp. 437-445.

[29] Aubert, H., Physiologie der Netzhaut. p. 136.

[30] Chodin, A. Ueber die Empfindlichkeit für Farben in der Peripherie der Netzhaut. A. f. O., 1877, XXIII,$_2$, pp. 177-208.

[31] Lamansky, S. Ueber die Gränzen der Empfindlichkeit des Auges für Spectralfarben. Pogg. Annal., 1871, CXLIII., pp. 633-643.

decreased, and (b) that the j. n. d. of intensity is smallest, or the sensitivity is greatest in order for yellow and green, blue, and red. Dobrowolsky[32] in 1876 worked with the colors of the spectrum in central vision and at various points in peripheral vision. Employing standard and comparison fields, he altered the intensity of the comparison by rotating a Nichol's prism before the light-source until its intensity was just noticeably different from that of the standard. Considering that sensitivity varies inversely as the magnitude of the j. n. d., he found (*a*) that the sensitivity to the different colors decreases with increase of excentricity; and (*b*) that the comparative sensitivity for the different colors is the same in the center and in the periphery, that is, the order of sensitivity from greatest to least is in each case, blue, green, red. Later in 1881[33] he worked at seventeen different points in the intensity scale. He found again that the j. n. d. for blue is smallest, for green next, and for red largest. In addition he found that the ratio of sensitivity between any two colors as measured by the j. n. d. is not the same for different points in the intensity scale.

In regard to the methods used in the investigations reported above, it may be noted that in no one of the cases have the intensities of the stimuli used been measured and standardized. Tests of the comparative sensitivity of different parts of the retina to the same color and to different colors may be made with propriety by such methods, but not of a given part of the retina to the different colors. Conclusions can not, then, be drawn by the preceding investigators with regard to the comparative sensitivity either of the center or of the periphery of the retina to the different colors. They can, however, show that the center has not the same comparative sensitivity to the different colors that the periphery has. This conclusion may in fact be drawn from the results of all except Dobrowolsky. Dobrowolsky's results alone show that the center and periphery have the same relative sensitivity for all of

[32] Dorowolsky, W. Ueber die Empfindlichkeit des Auges gegen die Lichtintensität der Farben im Centrum und auf der Peripherie der Netzhaut. Pflüger's Archiv., 1876, XII, pp. 441-471.

[33] Dobrowolsky, W. Ueber die Veränderung der Empfindlichkeit des Augen gegen Spectralfarben bei wechselnder Lichtstärke derselben. Pflüger's Archiv., 1881, pp. 189-202.

the colors with which he has worked. A fair test of the comparative sensitivity of the eye to the different colors demands either that stimuli of equal energy be used or that the sensitivity be estimated in terms of units that can be compared. So far as the writer knows, no test of the sensitivity of the retina to color has ever been made with stimuli representing equal amounts of energy. Langley (1889) worked with stimuli of equal energy, but his test was for visual acuity.[34] Until stimuli of equal energy are used, it will remain an open question whether or not the retina, either in the center or in the periphery, possesses a different degree of sensitivity to each of the colors.

(3) *The effect upon the limits of sensitivity.* That change in the intensity of the stimulus has an effect upon the limits of sensitivity, has been shown by Abney[35] and others. Abney carried on an elaborate series of experiments with spectral light to show the effect of changes of intensity upon the extent of the color fields. He decreased the intensity of the stimulus by placing before it a gelatine wedge in the form of an annulus or ring. This annular wedge was one inch broad. It was graduated in thickness and its transparency was further regulated by black opaque particles which had been mixed with the gelatine in its semi-fluid state. The value of light admitted at O or at the thinnest part of the ring, was 10,000 units;[36] that admitted at 360° was 8 units. By interposing the annular wedge in a plane perpendicular to the path of the light and producing the proper amount of rotation, the intensity of the stimulus was reduced by graded amounts. Abney concluded that there is a simple relation between the intensity of the stimulus and the size of the color field.

The extreme position with regard to the effect of intensity upon the extent of the color field is taken by Landolt in the following passage. "In ein absolut dunkles Zimmer fiel nur durch eine kleine Öffung im Fensterladen directes Sonnenlicht. Dieses wurde auf das äusserste Ende des Perimeterbogens gelenkt. Während wir unser Auge ins Centrum des Bogens setzen, bracht man in die

[34] For discussion of Langley's work, see this paper p. 71.

[35] Abney, W. op. cit., pp. 155-195.

[36] No statement of the value of these units is made by Abney.

kleine, intensive beleuchtete Stelle farbige Papiere von möglichster Intensität der Färbung. Nun bewegtet sich das Auge langsam vom entgegengesetzen Ende des Bogens nach Scheitelpunkte zu und es zeigte sich dabei, dass wenigstens mit der innern Netzhautpartie alle Farben schon bei 90° erkannt wurden. Die Grösse des Objectes betrug weniger als 1 cm².

"Als dieselben Prüfungen auch mit Spectralfarben zu machen, entwarfen wir ein Sonnenspectrum im sonst dunkeln Zimmer und liessen es durch eine achromatische Linse auf einen Ende des Perimeters befindlichen Schirm fallen. Dieser hatte eine verändliche Spalte, mittelst welcher man die einzelnen Farben aus dem Spectrum isolieren konnte. Während wir nun wiederum nach langer Adaptation, und bei verbundenem zweiten Auge das eine Ende des Bogens fixierten, würde von einem Assistenten irgendeine Farbe des Spectrums auf die Spalte gelenkt, und wir drehten nun, unter stehter Fixation unserer Fingerspitze, welche sich auf dem Bogen bewegte, das Auge allmählig der Farbe entgegen. Es zeigte sich auch hier wiederum dass alle Farbe schon bei 90° erkannt werden, wenn sie intensiv genug sind."[37]

The first to recognize the need for making any sort of intensity equation of the stimuli used to investigate the relative sensitivity of the retina to the different colors was Ole Bull.[38] His purpose was to find an accurate method for investigating and measuring the sensitivity of the retina to the different colors. The first essential condition of the method, he considered, must be to equate the colors in saturation and brightness. Briefly, his method of equating in saturation consisted of using complementary colors of such relative intensity that they cancelled each other in a 1:1

[37] Landolt und Snellen. Ophthalmometrologie. Handbuch der ges. Augenheilk. von Graefe und Saemische, 1874, III., p. 70. The above quotation is given in full in the original in order to confirm (a) the statement made p. 16 concerning the interpretation of Aubert's statement of Landolt's results, and (b) the writer's interpretation, as opposed to Baird's, of Landolt's results, stated p. 18.

A brief summary of the above work is given by Landolt in Klinische Monatsblätter für Augenheilkunde, 1873, XI., pp. 376-377; and in Annales d'Oculistique, 1874, LXXI., pp.44-46.

[38] Bull, O. Studien über Lichtsinn und Farbensinn. A. f. O. 1881, XXVII, pp. 54-154.

ratio; that is, he used colors whose color-cancelling or color-quenching power was equal. It will be shown later in the paper (pp. 63-69), that this method is an anomoly, and, so far as the writer knows, is not justified in any investigation of color sensitivity that has yet been proposed. It certainly does not warrant conclusions concerning the relative limits of color nor the relative sensitivity of the retina to the different colors. Using this method of equating Bull concludes, however, that the retina, central and peripheral, is most sensitive to blue, then to yellow, then to red and green.

The second to recognize this essential condition was Hess[39] who made an exhaustive "Prüfung des Farbensinnes auf der peripherischen Netzhaut." Hess's object was primarily to furnish Hering with experimental evidence that would enable him to refute the Young-Helmholtz theory as modified by Fick to explain color-blindness. Young's view that congenital color-blindness is due to the absence of one of the three kinds of nerve fibres conceived by him to exist in the retina was adopted by Maxwell and Helmholtz, and extended by the latter[40] to explain the so-called peripheral color-blindness of the normal eye. Helmholtz believed that the peripheral retina is red-blind, and that this fact could be explained by assuming the absence of the red-sensing fibre. In 1873 Fick[41] and Leber[42] independently pointed out that this explanation of the peripheral color-blindness is inconsistent with the fundamental assumptions of the Young-Helmholtz theory. Fick declared that according to this theory the sensation of white can be aroused only by the stimulation of all three fibres in equal amounts, or to express it in another way, in balanced proportions. Now, if one fibre were inactive in the

[39] Hess, C. Ueber den Farbensinn bei indirectem Sehen. A. f. O., 1889, XXXV, pp. 1-62.

[40] Helmholtz, H. Handbuch der physiologischen Optik. 1st ed., 1867, pp. 301, 845.

[41] Fick, A. Zur Theorie der Farbenblindheit. Arbeiten aus dem physiol. Laborat. der Würzburger Hochschule, pp. 213-217.

[42] Leber, T. Ueber die Theorie des Farbenblindheit und über die Art und Weise, wie gewisse, der Untersuchung von Farbenblinden entnommene Einwände gegen die Young-Helmholtz'sche Theorie such mit derselben vereinigen lassen. Klin. Monatsblätter f. Augenheilk., 1873, XI, pp. 467-473.

peripheral retina, the sensation of white could never be produced in that part of the retina; but instead, the sensation proper to the combined action of the other two fibres would be aroused by white light. If, for example, in the middle region of the retina, the red-sensing fibre, and in the more peripheral regions both the red- and the green-sensing fibres were lacking, the sensation produced by white light in the former case would be blue-green, in the latter blue.[43] Further, if one or more fibres were absent in the outer zones of the retina, all the color sensations in these regions would be more saturated than those in the more central regions. For when all three fibres are present, as in the central retina, red, green, or violet light, for example, will stimulate not only its own proper fibre strongly, but will also stimulate the other two weakly. A certain amount of this total stimulation will be in the proportion to give the sensation of white, or more properly speaking, the sensation of gray, and the effect of this colorless component will be to reduce the saturation of the color sensation aroused. If, then, in the peripheral retina only one or two fibres are present, the colorless component will not be present to reduce the saturation of the color sensation, hence, other things being equal, the sensation of color should be more saturated here than that given in the central retina. Fick proposed the following modification of the theory to account for the color phenomena of the peripheral retina. He assumed that from the middle toward the periphery of the retina the relative excitability of the three nerve fibres to lights of the various wave-lengths constantly alters in such a way that at a certain distance from the fovea, namely, in the zone called by Helmholtz red-blind, the red-sensing fibres possess the same excitability as the green-sensing fibres toward lights of all wave-lengths;

[43] While in the opinion of the writer, Fick is correct in saying that white could not be produced in the extreme periphery by the action of two of the retinal fibres he is not right in saying what would be produced. For by a literal interpretation of the curves of excitation drawn by Helmholtz to represent his theory, none of the color experiences can be produced by the action of two fibres, excepting those in a small region of the spectrum in the violet. All other color experiences are produced by the combined excitation of all three fibres in some proportion.

and that further toward the extreme periphery, all difference between the relative excitability of the three fibres diminishes and finally disappears. In the red-blind zone, then; the intensity-curves for the red- and green-sensing fibres coincide, and in the totally color-blind zone, the curves for all three coincide. Curves drawn in accord with these assumptions will, it is contended by Fick, explain the types of color-blindness found in the peripheral retina without violating any of the fundamental principles of the Young-Helmholtz theory. Helmholtz accepts the essential points of this modification and incorporates them in his theory in his later edition of the Physiologische Optik.[44]

In order to disprove Fick's assumption that the relative intensity of response of the three fibres varies from center to periphery of the retina, and thus discredit the Helmholtz theory, Hess advanced three lines of argument. These arguments are as follows. In the first place he claims that there are three colors of the spectrum, a yellow, a green, and a blue, and a mixed color, a bluish-red, which are all invariable in tone from the center to the periphery of the retina.[45] In the second place, he shows that the proportions in which the complementary colors combine to produce white do not change for the different parts of the extramacular retina. And in the third place he attempts to show that a constant ratio of sensitivity to the members of each pair of complementary colors obtains throughout the retina. In order to make his third point he attempted to obtain red and green stimuli such that the red *Valenz* of the one, or, as he defines *Valenz,* its capacity to arouse red sensation,[46] should equal the

[44] Helmholtz, H. Handbuch der Physiologischen Optik. 2nd ed., 1896, p. 373.

[45] For a refutation of this point see footnote, p. 85.

[46] Hess defines the *Valenz* of his stimuli as their power to arouse color sensation. The writer would question this use of the term. According to its accepted chemical usage, the term might be applied with some degree of propriety to the power which, in terms of the Hering theory, a color possesses to combine with or cancel its complementary color, but scarcely to its power to arouse sensation. Hess, we presume, applies this term to the power of a color to arouse sensation because he assumes that this power is the same or at least equivalent to its power to cancel the complementary color. But since, as we shall show later (see p. 65), this assumption is far from correct, we strongly question the propriety of calling the power of a color to arouse sensation its *Valenz.*

green *Valenz* of the other. He describes his method of doing this as follows: "Als das Nächstliegende erscheint es nun, einen roth- und einen grün-wirkenden Pigmente den gleichen Roth- und Grünwerth dann zuzuschreiben wenn dieselben zu gleiche Theilen, z.B. auf dem Kreisel gemischt eine farblose Mischung geben" (p. 39). The same procedure was used in obtaining his blue and yellow stimuli. Using as stimuli, then, a red equal in cancelling power to a green, and a blue to a yellow, he determines the limits of sensitivity to these four colors. He finds that the limits for his red stimulus coincide with the limits for his green, and the limits for his blue with the limits for his yellow. The limits for blue and yellow, however, fall further out from the fovea than they do for red and green. From these results he concludes (*a*) the sensitivity of the retina from center to periphery falls off with the same rapidity for red as for green, and for blue as for yellow: and (*b*) the sensitivity for both red and green falls off more rapidly than for blue and yellow. Among his conclusions one also finds: "Bei den von uns mitgetheilten Untersuchungen ist die Prüfung des Farbensinnes auf der peripheren Netzhaut zum ersten Male mit genauer Berücksichtigung aller jener Bedingungen vorgenommen worden, welche unverlässlich sind wenn die mit verschiedenen Farben gewonnenen Resultate untereinander vergleichen werden sollen" (p. 56). These conclusions are open to the following criticisms: (1) His results do not warrant the statement that the sensitivity for red falls off as rapidly as for green, and for blue as for yellow. For this statement is based on the assumption that if in passing from center to periphery, sensitivity ends at the same point on the retina for two stimuli which have equal power to arouse sensation at the center, they must still have equal power to arouse sensation at the periphery, that is, sensitivity has fallen off as rapidly for one as it has for the other. Now in the first place this assumption begins with a fallacy. For his stimuli were not equated in power to arouse sensation but in cancelling power, and, as we shall show later, the power of a color to arouse sensation and its power to cancel its complementary color are not at all equivalent. And in the second place the assumption is itself incorrect,

for, because of the abrupt decrease in sensitivity as the limits are approached, the relative sensitivity to the two colors may have changed greatly and still their limits have coincided. We have found for example that working with colors of normal saturation under good illumination, it takes, varying with the color, a difference of 90° to 120° of color to make a difference of 1° in the limits. Hess should have determined the limens of color at various points from the center to the periphery of the retina, and have found out whether the ratios of the liminal values of his pairs of stimuli were equal at all of these points.[47] If so, the sensitivity to each member of the pair must have fallen off with equal rapidity from point to point, otherwise a change of ratio would have occurred. This method would have had the following advantages. (*a*) Account would have been taken of sensitivity at a large number of points from fovea to limits. (*b*) Much smaller changes in sensitivity would affect the limens than would affect the limits, especially until very near the limits. (*c*) No equation of stimuli with its attendant disadvantages would have been needed as long as the liminal values for each color were obtained in terms of the same stimulus all the way out. (2) But even if an equation made in terms of cancelling power were the equivalent of an equation made in terms of the power to arouse sensation, he would not have been justified in concluding, so far as his method of working is concerned, that the red-green sense decreases more rapidly than the blue-yellow sense, because this method afforded him no means of equating the intensities of the members of one of the pairs with those of the other pair. (3) Nor is he justified in his claim that he is the first to investigate the color sensitivity of the peripheral retina who has paid due regard to all the conditions which are essential if the results obtained for this sensitivity are to be compared with one another. One scarcely knows where to begin to refute a

[43] While in the opinion of the writer, Fick is correct in saying that white just noticeable difference of sensation could have been determined at each of these points in the retina for various points in the intensity scale. An account could thus have been had of the retina's sensitivity to the members of the pairs of colors at as many degrees of intensity of sensation as was desired.

statement so broadly overdrawn as this. The inadequacy of his treatment of the factors: general illumination, brightness of the stimulus, brightness of the surrounding field and preëxposure, is obvious to anyone who knows the effect of these factors. This inadequacy, however, will be noted at various other points in the paper. It will be sufficient at this point to consider only his handling of the factor, intensity, and that only briefly, for it will also be discussed in some detail at another point in the paper. Hess's problem was narrow and happens to furnish one of the very rare cases in which a subjective equation of the intensity of the stimuli used is justified. But his conclusion with regard to his method of handling the intensity factor is broad and specifically refers to all investigations of sensitivity in which results are to be compared. Such a conclusion is most assuredly not justified. In fact one might almost say that the converse of his conclusion is true. In no investigation of the comparative sensitivity of the retina to the different colors where absolute values are wanted is a subjective equation permissible. Such an equation begs the question at the outset. In such an investigation when an equation is needed, it should be made in terms of a common objective unit, for example, the unit of energy, and when an equation is not needed, the sensitivity should be estimated and expressed in terms of this common objective unit, or some other unit in terms of which results can be compared. In no case, so far as the writer is at present able to outline the field, is a subjective equation justified in an investigation of sensitivity except in certain problems relating to existing color theories or assumptions made for systematic purposes. And not even in these problems, so far as the writer is familiar with them, is an equation made in terms of cancelling power justified in an investigation of sensitivity.

Hegg[48] was the third investigator to attempt intensity equation. He posits three conditions to be fulfilled "für die Untersuchung des peripheren Farbensinnes." (*a*) The colors must be physiologically pure, that is, each color must be sensed similarly in all parts of the retina sensitive to it. (*b*) The colors must be

[48] Hegg, E. Zur Farbenperimetrie. A.f.O., 1892. XXXVIII., pp. 145-168.

of equal value in regard to brightness. (*c*) They must be equal in regard to color content (farbigen Gehalt). Concerning the third condition, Hegg writes: "Wenn es sich nun, was von theoretischen und praktischen Gesichtspunkten aus betrachtet von gleich grosser Wichtigkeit ist, darum handelt, die verschiedenen Farbempfindungen mit einander zu vergleichen, die physiologische Erregbarkeit entsprechender Nervenelemente nach einem gemeinsamen Massstab zu messen, so ist es selbstverständlich unumgänglich nothwendig, mit gleichgemessenen Reizen die Versuche anzustellen und unsere definirbaren, invariablen Farben anzupassen" (pp. 148-149). Hegg's "gleichgemessene Reizen" were obtained according to the method first used by Bull and endorsed by Hess. But this method of equating can not warrant any conclusion concerning the relative limits of peripheral sensitivity to the different colors. Hegg is then not justified in concluding "dass die Grenzen für Roth und Grün zusammenfallen. Die Grenze für Gelb sind durchwegs ca. 1° enger als für Blau, vielleicht wegen der stärkerem Brechung der blauen Strahlen?" (p. 166).

Baird[49] was the next to use this method of equating. He determined the relative extension of the different color zones, employing as stimuli light transmitted through gelatine filters. Like his predecessors he also concludes beyond what is justified by his method of working. He expresses his results as follows: "The zone of stable red is coextensive with that of stable green; the zone of stable yellow is coextensive with that of stable blue; and the yellow-blue zone is much more widely extended in all directions than is the red-green zone" (p. 61).[50]

[49] Baird. loc. cit.

[50] Fernald (Psychol. Rev. Monog., 1909, X, pp. 60-67) as a minor point in her study of the color sensitivity of the peripheral retina, made a hurried investigation in the nasal and temporal meridians of the limits of an Urroth and an Urgrün, an Urgelb and an Urblau that she claimed were of equal saturation. Her method of equating these stimuli was the same as that of Bull, Hess, Hegg, and Baird. The limits of these stimuli were, she states, determined hurriedly, most of the observations being made at intervals of 5° on the peripheral retina; for example, she states that Urgelb and Urblau were both seen at 85°, and not seen at 90°. In spite of the looseness of these determinations, she concludes that "the limits for the Urgrün are practically coextensive with those for the Urroth, and the fields for the

Bull, Hess, Hegg, and Baird all claim, then, that when the investigation is made with stimuli equated in brightness and in terms of cancelling power, the limits for *Urroth* and *Urgrün,* for *Urgelb* and *Urblau* coincide. It may be inferred from their work that they believe that at least one of the reasons for the non-coincidence of limits obtained by previous investigators is that the colors used were not equated in intensity. Evidence, however, can be derived from the work of Kirschmann,[51] 1893, that this can not at least be considered the sole reason. In Kirschmann's case, in fact, it apparently can not be considered as having any influence at all in producing the non-coincidence obtained. Although his pairs of colors were not equated in intensity, it is obvious that the deviations he obtained from coincidence of limits can not be explained as due to differences in intensity between his stimuli. Kirschmann mapped many meridians of the retina for the limits of sensitivity with both spectral and pigment stimuli. The pairs of colors were not equated in intensity. His color maps show that the outline of the field for each color is irregular in the different meridians, and is different from that of any other color. In general the field for blue is wider than that for yellow, but in certain meridians this order is reversed. The red field is generally wider than the green, but in some meridians the green is the same or wider than the red. Further, the difference between the limits of the colors in some meridians is considerably greater than in others. It is evident

Urgelb with those for the Urblau" (p. 65). In addition to applying to this work the criticisms passed above concerning the more careful work of Bull, Hegg, and Baird, all of whom drew conclusions similar to Fernald's, one may express surprise that work so sketchy should be considered as warranting any conclusion whatever. Fernald states, however, that differences of 5° in limits are too small to be of any significance (p. 66). She makes this statement apparently because with the varying conditions of illumination under which she worked, 5° seem to be a normal variation in limits. (It may be too that she considers that this gives her warrant for working only at intervals of 5°.) But as will be shown in the experimental section of this paper, a difference of 5° in limits represents a difference in sensitivity sufficient to raise the limen of sensitivity 200°. In more careful work, then, limits which varied 5° would hardly be considered as "practically coextensive."

[51] Kirschmann, A. Die Farbenempfindung bei indirectem Sehen. Philos. Studien, 1893, VIII., pp. 562-614.

that irregularities of this kind can not be due to a difference in the intensity of the stimuli employed, for if blue and yellow, for example, have the same limit when equated in intensity, their limits should retain the same general outline when the colors are of unequal intensity, and should differ only in their distance from the fovea. The zone for the more intense color should in every meridian be regularly some degrees wider than that for the less intense. Relative to the issue between Kirschmann and Bull, Hess, Hegg, and Baird, it is interesting to find that Bull, Hess, and Baird, who all claimed to find coincident limits in all parts of the retina for the paired colors obtained results which, when examined in detail, show the same deviations from coincidence as those which Kirschmann found. Baird, for example, determined the limits of the four principal colors in eight meridians, and concludes: "The results show that the zone of stable-red is coextensive with that of stable-green; that the zone of stable-yellow is coextensive with that of stable-blue."[52] An inspection of his table of results shows however, that this coincidence is extremely rough. In the results for every observer it is found that in some meridians the green field is wider than the red by 1°, 2°, or 3°; in other meridians, there is coincidence of limits; and in still other meridians, the green field is narrower than the red by 1°, 2°, or 3°. The same thing is true of blue and yellow. In general, but not in every meridian, yellow seems to be wider than blue on the nasal retina, blue wider than yellow on the temporal. Hess's and Bull's results show similar variations which are in some cases of even greater extent. It is evident, however, from their conclusion concerning the coincidence of limits that they regard these variations as insignificant, probably no more than their normal M.V. for the rough conditions under which they worked. But it should be borne in mind that 2° or 3° of difference in limits is not insignificant when conclusions are to be drawn from the results with regard to the relative sensitivity of the peripheral retina to the members of the pairs of complementary colors. Because of the abrupt falling off in sensitivity just before the limit is reached (see p. 117 ff.), a difference of

[52] Baird, J. op. cit., p. 61.

2° or 3° in the limits represents quite a large difference in sensitivity. For example, according to our results a difference of 2° in limits represents a difference in sensitivity sufficient to raise the limen for yellow 120°, for green 100°, for red 160°, for blue 170°; and a difference of 3° represents sufficient to raise the limen for yellow 210°, for green 215°, for red 210°, for blue 215°. Obviously the point is too important to be passed over without re-examination by better methods of working. The limits should be re-determined under conditions that do not give so large an M.V. This has been done by the writer with such a control of all the factors that cause variable results that her M.V. from observation to observation is less than 1°. The results obtained show that this difference in limits is real, and not an error due to any inaccuracy in the method of working. In some meridians the limits coincide, in others they diverge. In short, when the zones are outlined by lines connecting the points representing the limits in the different meridians, these lines for the pairs of colors do not coincide, but criss-cross in a very irregular manner. Therefore, on the basis of our own results as well as those of Kirschmann, the inference can not be drawn from the work of the men who have equated their stimuli in terms of cancelling power that coincidence of limits had not been obtained up to that time because stimuli so equated had not been used. Nor can the conclusion be drawn that even if the stimuli had been properly equated, coincidence of limits would have been obtained. In fact the converse of this conclusion can apparently be drawn.[53]

[53] The writer used as stimuli in these experiments the standard yellow, red, green, and blue of the Hering series. She did not use colors stable in tone as Bull, Hess, Hegg, and Baird claimed to use, because an exhaustive study of this question showed her that stability of tone for all meridians of the retina can be obtained for blue alone of the four principal colors. For a further statement in support of this point, see footnote p. 85. In any event, she is unable to see how the fact that the red and green of this series appear yellow in a small region of the peripheral retina could have any effect on the coincidence of limits for red and green, unless the limit for red, for example, is taken as the point at which all sensation of color disappears, regardless of whether this color is red or yellow. (The writer considered in her own experiments that the limit for a color was the point at which the color sensation lost all trace of its original quality.) However, even if the point at which all sensation of color whatever disappeared be

Therefore, the argument based upon it against Fick's modification of the Helmholtz theory to explain the color-blindness of the peripheral retina can also be refuted insofar as the results on the coincidence of limits can be considered as furnishing argument. This argument is, it will be remembered, that the sensitivity of the retina from fovea to periphery falls off as rapidly to one of the members of the pairs of complementary colors as to the other. It should be borne in mind, however, that the results needed in order to make this argument can not be obtained by a determination of the comparative limits of sensitivity alone.

considered the limit, the following consideration shows that the small component of yellow present in the peripheral retina in the sensations aroused by the red and the green of this series could not have caused the criss-crossing of limits any more than a difference in intensity could have caused it. In fact the point in reality reduces to a question of intensity. If, for example, one of the colors were stronger than the other, this color would have relatively more power to arouse this yellow component, than it would if the colors were of equal intensity. That is, the zone through which the yellow component would be sensed would be broader for this color than it would have been had both colors been of the intensity of the weaker color. And relative to the zone in which a yellow component was sensed, it would not be irregularly broader in some meridians for the stronger color and in other meridians for the weaker color, for in regions in which the yellow sense is relatively weak the zone would narrow for both stimuli. In short, while the influence of the yellow component might cause the zone of sensitivity to broaden for one member of the pairs of stimuli as compared with the other member, it could not cause it to become alternately broader and narrower, in other words, to criss-cross. It is just as obvious that difference in brightness can not be offered as an explanation of this criss-crossing, even if difference in brightness could be shown to have an effect on the limits of sensitivity to the pairs of colors in question. But, as we will show in the experimental section, difference in brightness can be considered as having no effect whatever on the limits of sensitivity. Hence on both counts, difference in brightness can be ruled out of consideration. It would seem, then, that we can conclude that the criss-crossing of limits represents a real relation of sensitivity to the members of the pairs of colors in the far periphery of the retina, even before the investigation is made with stimuli properly equated in intensity. Moreover, when we take into account the fact that a difference of 2° to 3° in the limits represents a large difference in sensitivity we have considerable reason for believing that the ratio of the sensitivity to one member of a pair of complementary colors to the sensitivity to the other member is not the same in all parts of the retina. The point will be definitely determined in the near future by the writer by a careful determination of limens from point to point in many meridians of the retina, with stimuli which consist of lights of spectral purity, measured in terms of a common unit of intensity.

Knowledge is needed of the comparative sensitivity all the way out. Moreover, this knowledge must be based on actual determinations at points not widely separated from each other. The limit is only one of the points at which determinations should be made. In fact, it can scarcely be said to sustain any more important relation to the problem than any other point far removed from the fovea. Furthermore, conclusions can not be drawn from work done by the method of limits with regard to the comparative falling off in sensitivity from fovea to periphery unless it has previously been inferred from a comparison of the results at the center with the results at the limits what the comparative sensitivity should be at the points intervening, as was done by Hess. But this is wholly unjustifiable, for if there is one principle above another that the determinations of sensitivity in the peripheral retina bring out, it is that inferences can not be drawn about sensitivity between points at all widely separated. In fact, practically no conclusions of systematic importance can be justified at all from results obtained by the method of limits, although conclusions of great importance to theory have frequently been drawn from such results. The method of limens should be used instead, for by means of it accurate account can be taken of sensitivity at any point that is desired.[54]

A brief survey of our discussion of intensity shows the following facts:

1. The intensity of the stimulus is a factor influencing both the limens and the limits of color sensitivity. It should, therefore, be carefully standardized in all determinations of sensitivity.

2. The conclusions that have been drawn up to this time concerning the comparative sensitivity of the retina to the different colors have not been justified because of the methods of working that were used in the investigations from the results of which they were drawn; for (*a*) either no standardization of the intensity of the stimuli used had been made; or (*b*) this standardization had been made by an improper method. From the results of

[54] As stated in footnote p. 83, if a more exhaustive study of the point is wanted, the results of the method of limens should be supplemented by a determination of the just noticeable difference in sensation for various points in the intensity scale at each point of the retina investigated.

the work as it was done the following conclusions alone can be drawn: (*a*) The comparative sensitivity to the different colors is not the same at the center as it is in the periphery of the retina. This conclusion may be drawn from the results of Chodin and Raehlmann and Butz for the limens of sensitivity. And (*b*) it is not the same for the members of the pairs of complementary colors at all points even in the small region of the peripheral retina that has been examined, namely in the region comprehended by the criss-crossing limits for these colors. This conclusion may be drawn from Kirschmann's results, from our own, also from those of Bull, Hess, and Baird as shown in their tables giving the limits of their stimuli in different meridians.

3. Broader conclusions than this are justified only when the comparative sensitivity of the retina to the different colors is determined with stimuli properly standardized in intensity. As has been briefly pointed out, the comparative limits of sensitivity can be determined only when the intensities of the stimuli used have been standardized in terms of a common objective unit, for example, the unit of energy; and the comparative limens only when the intensities of the stimuli used have been estimated in terms of this common objective unit, or some other unit in terms of which results can be compared.[55] This point will be discussed more fully later in the paper (see p. 63 ff).

(*c*) *The effect of brightness of the stimulus.*

There has been very little discussion by previous investigators whether the brightness or white-value of a color affects the retinal limits of sensitivity to that color, and whether this aspect of the stimulus need then be taken into account in determining the relative extent of the color zones. We have already shown that in such work as there has been, the brightness factor has been obscured by and confounded with the intensity factor.

The confusion of the intensity and brightness aspects of color was noted by Langley in an article entitled *Energy and Vision, Philos. Mag.*, 1889, XXVII, 5th ser., p. 1. Langley writes: "While it is quite a familiar fact that the luminosity of any spectral ray increases proportionately to the heat in

[55] It is scarcely needful to point out that the same kind of standardization is required in order to determine the comparative j. n. d's. for the different colors.

this ray, and indeed is but another manifestation of the same energy, I have recently had occasion to notice that there is, on the part of some physicists, a failure to recognize how totally different optical effects may be produced by one and the same amount of energy according to the wave-length in which this energy is exhibited. I should not perhaps have thought it advisable to make this last remark, were it not that there has appeared in a recent number of *Wiedemann's Annalen* a paper by H. F. Weber on "*The Emission of Light*", in which he tacitly makes the assumption that the luminosity of a color is proportionate to the energy which produces it, an assumption which it is surprising to find in a paper of such general merit and interest."

This confusion, insofar as it has not been due to a misinterpretation of terms, seems to have arisen because the usual method of varying the one factor has necessitated an accompanying variation of the other. Further, the fact that when the intensity or energy of spectral light is increased to a maximum, the color is lightened until white is produced,[56] has been responsible for the view that light colors are more intense than dark colors, and has led to the custom of determining the energy or intensity of colored light by photometric methods. The photometric method can not, however, be used directly for estimating the intensity of colored light for two reasons. (*a*) Direct radiometric measurements of energy show that the relative values of the colors of the spectrum as determined by the two methods do not at all coincide. The photometric curve, for example, of the spectra of all light sources of normal intensity is highest in the yellow-green and lowest in the blue and red. The radiometric curve of the visible spectrum of sunlight of the same intensity is, on the other hand, according to Langley,[57] highest in the red near the C line and lowest in the violet; while the radiometric curves of the visible spectra of most of the artificial sources of light, such as the Nernst, tungsten, and arc lights, are highest in the extreme red and lowest in the violet. (*b*) The relative photometric values of the colors of all spectra differ widely for different intensities of the same light-

[56] This statement is true only if the original color has maximal saturation. When one increases the intensity of colors whose original intensity is slight, red and yellow become lighter, blue and green darker. These brightness changes are known as the Purkinje phenomenon.

[57] Langley, Energy and Vision. Amer. Journ. of Science, 1888, XXXVI, 3rd Ser., pp. 359-379; also Philos. Mag., 1889, XXVII, 5th Ser., p. 1; and Invisible Solar and Lunar Spectra, Philos. Mag., 1888, XXVI., 5th Ser., pp. 505-520.

source. For medium intensities, for example, the curve is highest in the yellow-green and lowest in the blue. But as the intensity is decreased the curve levels, while its maximum height shifts to the green and its minimum to the red. In short, the photometric value of a color is not a constant but a variable function of its intensity. From the above consideration, it is obvious, then, (*a*) that the photometric method can not be used to estimate the relative intensities of the colors of the spectrum even for a single intensity of light-source unless for each point of the spectrum considered a factor be determined which will transform the photometric into the radiometric value; and (*b*) that it can not be used over a wide range of intensities of light-source unless this calibration be previously made for each degree of intensity used. Furthermore, the brightness factor is not inseparably bound up with the intensity factor. It can be isolated. When, for example, one uses a constant amount of colored light, spectral or pigment, and mixes with it a constant amount of white, black, or gray, one obtains stimuli which contain an equal amount of colored light but which have different brightnesses. Up to the present this method of isolating the brightness factor to test its influence has been employed only by Hess, and in his work, as we shall see, it has been used very inadequately.

The discussion whether the brightness of the stimulus affects color sensitivity was raised by Aubert. Aubert was unable to reach positive conclusions concerning its influence. He was led to a consideration of the question by the outcome of an investigation planned to determine the influence of visual angle upon the perception of color in central vision. His results showed that the liminal visual angle was different in case of the different colors, and further, that it differed when the colors were viewed upon white and black grounds. In the discussion of these results he writes: "Zum Theil beruhen diese Verschiedenheiten wohl auf einer verschieden starken Affection des Farbensinnes, zum grösseren Theil aber wohl auf Helligkeitsdifferenzen. Wir haben dabei drei Momente zu berücksichtigen, nämlich die Farbennüance, die Farbenintensität, und die Helligkeitsdifferenz oder den Contrast der Pigmente."[58] These *Momente* Aubert defines as

[58] Aubert, H. Physiologie der Netzhaut. Breslau, 1865, p. 111.

follows: *Farbennüance* is the sensation given when a color is mixed with white, black or gray. A light blue, for example, contains more white and less blue light than a saturated blue.[59] *Farbenintensität* is defined as "the impression which is dependent on the intensity of colors: in case of spectral colors, on the amplitude of vibration; in case of pigments, on the intensity of the illumination." "Maxwell," he says, "calls this *'shade'*: one color may be lighter or darker than another."[60] Whether or not Aubert also uses the term *intensity of color* as synonymous with *white-value* is open to question. There is evidence in his discussion, however, that he uses it synonymously with *brightness*. For example, when discussing *Farbenintensität*[61] he claims that the intensity factor cannot be made standard because it is impossible to determine which of two colors is the brighter, and because the photometric values of the spectral colors is unknown, the results of Melloni, Dove, and Helmholtz on this point differing widely. But whether or not *brightness* means for him also *white-value* depends upon what he thinks is measured by the photometric method. *Helligkeitsdifferenz* is the brightness relation between a color and its background.[62] The three factors, then, that Aubert believes we have to consider are (*a*) the amount of colorless light mixed with the color; (*b*) the intensity or brightness of the color; and (*c*) its contrast with the background. The first of these factors, he contends, influences color perception. He finds that the more colorless light is mixed with a pigment color, the the greater must be the illumination at which the color can be liminally sensed; in other words, when the pigment surface reflects a small amount of colored light, the intensity of its illumination must be proportionately greater to give liminal sensation.[63] The third of these factors he also considers very important. Colors have different limens and limits of visibility on white and on black grounds. Now the brightness of the

[59] Aubert, H. loc. cit.
[60] Aubert, H. op. cit., p. 108.
[61] Aubert, H. op. cit., p. 111.
[62] Aubert, H. op. cit., p. 112.
[63] Aubert, H., Untersuchungen über die Sinnesthätigkeit der Netzhaut. Pogg. Ann. d. Physik und Chemie, 1862, CXV, p. 111, 114.

color determines how great the difference is in the two cases. Blue, for example, is very dark. It is in great contrast to the white field and in much less contrast to the black. Its limit in each case is respectively 15° and 36°,—a difference of 21°. Red is less dark. Its limits with the white field is 16°, with the black 30°,—a difference of 14°. Green is a lighter color and more nearly of mean brightness between white and black. In this case the difference in its limits with white and black fields is only 4°. Aubert contends "dass die specifische Farbenwahrnehmung an der Seitentheilen der Netzhaut um so eher in eine blosse Wahrnehmung von Hell und Dunkel übergeht, je stärker dieselbe mit der Umgebung contrastiert."[64] This is stated again in the *Physiologie der Netzhaut:* "Contrast und Helligkeit der Farben sind von grossem Einfluss auf die qualitative Farbenempfindung, so wie auf die Grösse der Netzhautparthie, innerhalb welcher die Farben empfunden werden sein."[65] In this regard, then, the difference in the brightness of the colors has an effect on color sensitivity only when the brightness of the surrounding field is made the same for all of the colors. But since it need not and should not be made the same for all of the colors in any investigation of sensitivity, unless the purpose of the investigation is to test the effect of surrounding field on the different colors, this case may be ruled out of consideration. The second *Moment,* the intensity or brightness of the colors, Aubert finds himself unable to isolate. He works with pigment stimuli and can not alter the intensity without at the same time changing the proportion of colored to colorless light reflected from his stimuli; or as he calls it, the nuance of the color. That is, in order to change the intensity of the color, he is compelled to change the amount of white, black, or gray mixed with it.[66] Further, he thinks it is often impossible to determine which of two colors is the brighter.[67] However, his experiments to determine the relative intensity of illumination necessary for the

[64] Aubert, H. Ueber die Grenzen der Farbenwahrnehmung auf die seitlichen Theilen der Netzhaut. A. f. O., 1857, III_{2}. p. 54.

[65] Aubert, H. Physiologie der Netzhaut. Breslau, 1865, p. 122.

[66] Aubert, H. op. cit., p. 153.

[67] Aubert, H. op. cit., p. 111.

liminal visibility of the different colors lead him to think that the brightness of color is not in itself a factor. In these experiments he finds that when the colors are arranged in order according to the intensity of illumination necessary for their perception, they are from least to greatest: orange, yellow, red, light blue, light green, blue, green. But when the illumination is decreased so that all the stimuli are seen as grays, they differ in brightness from light to dark in the sequence: yellow, light blue and green, blue, green, orange, red. Since the order differs in the two cases, he concludes that the differences in the perceptibility of the colors can not be due to their difference in brightness. He says: "Vergleicht man diese Ordnung der Farben nach ihrer Helligkeit mit ihrer Reihenfolge hinsichtlich ihrer Erkennbarkeit bei beschränktem Lichtzutritt, so sieht man, dass die Helligkeit der Pigmente nicht die Ursache seyn kann, dass diese oder jenes Farbenquadrat bei einer geringeren Lichtintensität farbig erscheint."[68] His final conclusion from this discussion of the three *Momente* is that the colors are not equally perceptible; but it can not be determined in how far this depends upon color tone, color intensity, or color nuance.[69]

In clearing the ground by the discussion of these three *Momente,* Aubert, then, finds himself utterly unable to answer the question: Does the brightness difference between two colors affect the sensitivity of the retina to these colors? because he can not isolate the factors involved for investigation. He, however, recognizes the possibility that brightness difference may affect color sensitivity and for this reason is inclined to think that his own may be only a rough determination. He writes: "To obtain a fine estimation, the influence of brightnesses must be eliminated; and pigments of equal intensity and nuance must be observed upon a background of the same brightness as the pigment. But we do not possess such pigments; and since the photometric value of prismatic colors is not known, an exact estimation of the liminal visual angle at which the colors can be sensed seems impracticable."[70] As will be shown later, Bull

[68] Aubert, H. Pogg. Ann. d. Physik und Chemie, 1862, CXV, p. 105.

[69] Aubert, H. Physiologie der Netzhaut. Breslau, 1865, p. 123.

[70] Aubert, H. op. cit., p. 112.

and Hegg take this statement as authority to equate colors in brightness for investigations of the peripheral limit of color sensitivity. It is obvious, however, that the statement contains no real authority for the equation of colors to be used even in investigations of color sensitivity in central vision, because Aubert confesses that he is unable to demonstrate whether or not the brightness of a color affects the retina's sensitivity to that color. He has merely expressed a belief that in fine determinations the equation should be made. Baird, as we have seen, also claims Aubert as authority for equation in brightness, but apparently he has not even this much basis upon which to rest his claim, for in Baird's long list of references to Aubert, none is found to the section containing the statement quoted above. This statement occurs in Aubert's discussion of the influence of visual angle on the perception of colors in direct vision (Physiologie der Netzhaut, pp. 108-115). Baird's references to the *Physiologie der Netzhaut* are pp. 89-105; 116-124. As has been shown on p. 13, Baird apparently gets his authority from a discussion in which Aubert is clearly concerned not with the white-value of color but with the total effect of changes in the general illumination. Furthermore, so far as the writer has been able to ascertain, Aubert nowhere else gives as much authority for equating in brightness as is contained in the statement selected by Bull and Hegg upon which to base their claim.

Aubert's opinion that the effect of the brightness of a color upon the retina's sensitivity to that color can not be determined was also held by Chodin who was unable to isolate brightness and intensity from each other.

Chodin writes:[71] "Es bleibt nur übrig die Farben bei gleicher Sättigung und bei mittlerer Lichtintensität zu vergleichen, und da sie unter dieser Bedingung von verschiedener Intensität sind (vielleicht sind die idealen Farben von gleicher Helligkeit, wie Hering sich vorstellt aber wir wissen dies nicht und können es nicht wissen) so liegt es sehr nahe anzunehmen, dass diese verschiedene Helligkeit eine constante Eigenschaft der Farbe selbst sei, welche, wenigstens in merklichen Grade, weder vermehrt

[71] Chodin, A. op. cit., p. 178.

noch vermindert werden kann ohne eine Veränderung des Charakters der Farben selbst herbeizuführen." Chodin goes on to point out one of the difficulties of attempting to obtain stimuli of equal brightness. In case of some of the colors, both spectral and pigment, a change of quality or tone takes place, when, in their state of greatest saturation, their brightness is altered. For example, spectral yellow when darkened gives a reddish-yellow or brown appearance, and the yellow of pigment paper, a decided olive-green appearance. Blue, when altered in brightness, appears reddish. These color changes have been recorded by Chodin, Brücke,[72] Hegg,[73] Rood,[74] and others. They are marked and are particularly troublesome in that the blue and yellow stimuli, which undergo the greatest changes in quality, are the stimuli that must be altered the most in order to be equated in brightness.

Ole Bull[75] was the first to mention the problem under discussion in its specific relation to the determination of peripheral color limits. He made no direct test of the influence of the brightness of the stimulus upon sensitivity, but quoted as authority for equating his own stimuli Aubert's statement that for fine determinations of color sensitivity brightness differences must be eliminated. Like Aubert, he was unable to show that the brightness of the stimulus constitutes a factor, but unlike Aubert he does not recognize the need for demonstrating this point. He thus equated his stimuli apparently without ever even having realized the need to investigate whether or not this equation should be made.

Hess[76] seems to have been the only investigator who has made any attempt whatever to determine whether a light and a dark color of equal intensity have the same or different limits of visibility in the peripheral retina. His test was simple and was applied only to one color. Using two stimuli, the one composed

[72] Brücke. Wiener Berichte, 1865, LI, p. 10.
[73] Hegg, E. loc. cit.
[74] Rood. On the Effects Produced by Mixing White with Colored Light. Phil. Mag., 1880, X., p. 209.
[75] Bull, O. op. cit., p. 93.
[76] Hess., C. op. cit., p. 42.

of 180° *Urgün* and 180° white, the other of 180° *Urgrün* and 180° black, he compared their limits in the horizontal temporal meridian. In each case the stimulus was exposed on a background whose brightness was the same as that of the darker stimulus. Hess found the limit of the dark green to be 25°, of the light green 13°. The value of this brief test lies in that it shows a recognition of the need to investigate whether or not the brightness of the stimulus affects the limits of sensitivity, before an attempt is made to equate in brightness. Hess's method of determining the influence of the factor is, however, open to criticism in two regards. In the first place he made no determination of the amount of brightness difference existing between the colors used. He arbitrarily altered the brightness of green 180° in both directions, that is, toward both black and white. He gives no reason for this choice of 180° of variation of the brightness component. He does not tell us, for example, whether it represents as much brightness difference as there exists between his stimuli, or whether it represents more, or less. If it had represented less, the test would not have possessed due rigor. If, on the other hand, it had represented more, the test would not have been fair for two reasons. (*a*) Brightness mixed with color inhibits color sensation. This inhibitive action is greater the nearer the brightness mixed with the color approaches white, and is less the nearer the brightness approaches black.[77] It is obvious, then, that the difference between the amounts of the inhibition of the color by the white and that by the black would increase as the amount of the brightness component increases. If, then, in the above test, Hess had mixed with *Urgrün* in turn amounts of white and black that represented a brightness variation greater than the brightness difference that exists between the standard colors, he would have had a greater difference between the amounts of inhibition in the

[77] As will be shown in the experimental section of this paper, this may be stated as a general law of the action of brightness on all colors for all parts of the retina with the exception of a region within 5° of the limits of sensitivity to red and yellow, as determined with stimuli of normal saturation and intensity. Within this narrow zone the saturation of red and yellow is reduced more, apparently, by black than by white.

color mixed with white and the color mixed with black, and consequently a greater difference between the intensities of the sensations aroused by them, than he would have had, if a brightness change equal to that existing between the standard colors had been used. His results, then, can not be taken as evidence that the proper amount of brightness change necessary to render the standard colors equal in brightness would change the limits of color sensitivity. Much less can they be taken to show that the amount of brightness difference actually existing between the standard colors acting in conjunction with the greater amount of light coming from the standard colors than from his weakened stimuli would affect the limits of sensitivity.

(*b*) In Hess's experiment, the color stimulus containing 180° *Urgrün* and 180° white, and that containing 180° *Urgrün* and 180° black both possessed less physical intensity than would stimuli in which less brightness variation had been made. That the degree of intensity of the stimulus is a potent factor in the determination of whether or not the difference in brightness between a light and a dark color of equal physical intensity affects the peripheral limit of sensitivity to that color will be shown in the experimental part of this paper (pp. 104 ff). The results of this work, however, may be anticipated briefly at this point. As has been stated, the action of white when mixed with color inhibits the apparent saturation of the color more than black does. The question under consideration is whether the apparent saturation of a dark color is sufficiently greater than that of a light color of equal physical intensity to widen the peripheral limit of sensitivity to the dark color. Now a determination of the limen of sensitivity to color at a number of points from the fovea to the limits of sensitivity to color shows that the sensitivity to a color decreases slowly from the fovea to a point about 5° within the limit of sensitivity to that color as determined with a stimulus of full saturation,—the point varying slightly for the different colors in its distance from the color limit. From this point on toward the limit, the sensitivity falls off very rapidly. A large increase in the limen is present from degree to degree in this region, often as great as 90° per degree of retina traversed. It

is obvious, then, that if the intensity of the colored stimulus is sufficient to cause its limit to fall within this zone of rapid decrease in sensitivity, the difference in saturation between a light color and a dark color of equal physical intensity would not be sufficient to cause a widening of the limits. On the other hand, if a smaller intensity of color were used so that the limit of the color occurred within the retinal region where color sensitivity alters but slightly from point to point, the greater apparent saturation of the dark color would be sufficient to allow the color to be visible at a point where the light color of less apparent saturation though of equal physical intensity is not sensed. Now the limen for the different colors when mixed with white at the point where the rapid decrease in sensitivity to each begins, is as follows: 120° of yellow; 130° of green; 135° of red; and 145° of blue. These values, then, represent the amount of color that would have to be had in the stimulus to which white had been added to make the limits of sensitivity to them fall just at the boundary between the zones of gradual and abrupt decrease in sensitivity. And since black inhibits color less than white, even less color would be required in the stimuli to which black had been added to make the limits fall at this point. For any amount of color greater than these values, the limits would fall within the zone of rapid decrease. One could, then, add white to his stimuli by amounts varying from 0° to 215°-240° for the different colors, and black in still greater amounts, and still work within the zone of abrupt decrease. And as long as one works within the region of abrupt decrease, the limits for the colors lightened and darkened by the above amounts will coincide. It need hardly be said that 215°-240° multiplied by two to express the variation in both directions, represents a much greater brightness difference than exists between the standard colors. On the other hand, for any amount less than the above values, the limits would fall in the zone of gradual decrease. Now Hess's stimuli contained less than this amount of color because his *Urgrün* contained only 244° of green and 116° of blue. 180° of this *Urgrün* would, then, contain but 122° of green and 58° of blue. The intensity of this stimulus was, therefore, so small that ac-

cording to our results the limits for both component colors would fall in the zone of gradual decrease of sensitivity. In this zone the greater saturation of the color when mixed with black would cause it to be sensed farther out than the color when mixed with an equal amount of white; that is, the limits for the darkened color would fall further from the fovea than the limits for the light color, as Hess found them to do. In this regard, too, then, it may be said that if in Hess's test, a brightness change was made greater than the brightness difference between the standard colors, and consequently a stimulus was used having smaller intensity than it would have had, if the proper brightness change had been made, the test would have been unfair because the degree of intensity of the stimulus is a factor determining whether or not there is a different limit for light and dark colors of equal physical intensities.

While it is sufficient for our point to show in what respects Hess is open to criticism for arbitrarily selecting 180° of brightness variation without making any determination of how much need be made, a word may be added to show that 180° of brightness variation is much more than was needed. For, the table in which Hess[78] states the values of the stimuli determined by different observers to be equal in cancelling-action and brightness, shows that in no case was a variation of more than 133° made in one direction, that is, toward either white or black. It is often difficult to see just how much variation was made, because in the majority of cases both black and white were added, hence the net variation was less than the value of either. For example, 105° of yellow, 60° of white, and 195° of black were found by one observer to be equal in cancelling action and brightness to 85° of blue, 84° of white, and 191° of black; for another observer, 200° of red, 48° of blue, 66° of black, and 46° of white were equal in cancelling action and brightness to 188° of green, 39° of blue, and 133° of black. But in no case is the variation in one direction more than 133°, or less than 91°. We may conclude, then, that by his choice of 180° of brightness variation by means of which to compare the limits of a light and

[78] Hess, op. cit., pp. 45-46.

a dark color of equal physical intensity, he has, roughly speaking, made his brightness variation one and one-half times greater and his intensity only four-fifths of what it should have been, judging from the greatest variation he had to make for his brightness equation. Either one of these items: the overestimation of brightness change or the underestimation of intensity is sufficient both to render his test unfair and, moreover, to account for a very considerable difference in the limits for color mixed with white and for the same color mixed with black.

The second point of criticism of Hess's test is in regard to his method of controlling the brightness of the surrounding field and of the preëxposure. He did not use the proper conditions of brightness of screen and of preëxposure card. He used a screen and a preëxposure which were of the same brightness as the dark stimulus, both in the tests with the dark and with the light color. There was, then, a considerable amount of white added to the light stimulus by contrast from the dark background and by after-image from the dark preëxposure over and above the white that was added by objective mixing. Thus while he aimed to add equal amounts of white and black to his pairs of stimuli, he really added much more white than black. Now, we have found that white subjectively aroused apparently has as much effect on the color excitation as white objectively aroused. His test was thus again rendered unfair by his lack of proper conditions with regard to the brightness of the surrounding field and of the preëxposure. The surrounding field and the preexposure should have been made in each case equal in brightness to the stimulus.

Hess does not appear to have realized the importance either of the brightness of the surrounding field or of preëxposure as factors influencing color limits. He generally equalized the brightness relation between stimulus and background because he seemed to think that accuracy of judgment was fostered thereby,—that one can more readily tell when the color has disappeared from a given stimulus when there is no brightness difference between the stimulus and the background to confuse the judgment.[79] The preëxposure he made of the same quality

[79] See Hess, op.cit., p. 25.

and brightness as the background. No reason was given for this procedure.[80] Thus in the above test, he overlooked the diminution in the intensity of the sensation aroused by the lighter stimulus due to the contrast from the surrounding field and to the after-image from the preëxposure,—a diminution which is also in itself sufficient to account for quite a large difference in the limits for a light and for a dark stimulus of the slight degree of intensity used by Hess. Hess's results, then, assuredly can not be considered as showing that the brightness difference between the normal colors affects their limits of sensitivity.

Hegg,[81] like Bull, made no test to determine whether the brightness of the stimulus constituted a factor in the determination of color limits. He gives no reason for the attempt he makes to equate in brightness, other than the fact that Aubert and Bull had mentioned the necessity for this procedure.

Baird was the next to state that the stimuli used to investigate the peripheral color sense must be of equal brightness. His reasons for making this statement have already been discussed in part (pp. 12-19) in order to show how the prevailing confusion with regard to terms has led to misinterpretation. To connect this preceding discussion with what is to follow, a few words to résumé will probably be of service here. It will be remembered that like Bull and Hegg, Baird made no attempt to determine whether or not the brightness or white-value of a color exerts an influence on the limits of sensitivity to that color. Unlike Bull and Hegg, however, he claims to be able to derive authority for equating stimuli in white-value from the work of many investigators,—primarily from that of Aubert,[82] Landolt,[83] and Abney,[84] but also from Raehlmann,[85] Chodin,[86] Klug,[87] Bull,[88]

[80] See Hess, c. op. cit., p. 44.
[81] Hegg, E. op. cit., p. 146.
[82] Baird, J. op. cit., p. 12.
[83] ibid, p. 16.
[84] ibid, p. 31.
[85] ibid, p. 17.
[86] ibid, p. 20.
[87] ibid, p. 20.
[88] ibid, p. 22.

Hess,[89] and Hegg.[90] With regard to these sources of authority, it has been shown (*a*) that Abney and Landolt do not even claim that brightness difference affects the sensitivity of the retina to color, and that Aubert does not in the references given by Baird; (*b*) that Bull and Hegg equated their stimuli in brightness merely because Aubert had expressed the belief that such procedure is necessary in making fine determinations of color sensitivity, but since Aubert was unable to demonstrate this necessity, their reason for making the equation has no value;[91] and (*c*) that Hess's test, upon the results of which he bases his conclusion with regard to the need to equate, was both incomplete and wrongly devised. We have yet to show, then, that no authority can be derived by Baird from the work of Raehlmann, Klug, and Chodin. A claim to authority was derived from the work of Raehlmann and Klug by misinterpretations similar to those made in the cases of Landolt and Abney. Raehlmann and Klug both worked with spectral light and sought to find the effect of decreasing the intensity of the colored light upon the limits of sensitivity. Raehlmann[92] decreased the intensity of his stimuli as follows: Light reflected from a heliostat was passed through a prism and the spectrum from this source was thrown upon a screen, which may be called screen$_1$, the distance of which from the light-source was kept constant. This screen contained an opening for the transmission of the colored light. The amount of light transmitted could be regulated by the size of this opening, and the quality could be regulated by shifting the position of the opening along the spectrum. The colored light fell upon a second screen, screen$_2$, so arranged that its distance from screen$_1$ could be varied. In two ways, then, could diminution of

[89] Baird, J. op. cit., p. 27.

[90] ibid, p. 29.

[91] As has been shown, pp. 40-44, Baird, as well as Bull and Hegg, might have had some justification in citing Aubert's authority on the question of brightness equation, from the latter's statement that all brightness differences must be eliminated from stimuli used to make fine determinations of color sensitivity. But this statement of Aubert's is not included in the references to Aubert from which Baird drew his authority.

[92] Raehlmann, E. Ueber Verhältnisse der Farbenempfindung bei indirectem und directem Sehen. A. f O., 1874, XX,,, p. 18.

intensity be produced: (*a*) by decreasing the size of the opening in $screen_1$, and (*b*) by increasing the distance between $screen_1$ and $screen_2$. Both methods were used by Raehlmann for producing what he terms *die Abnahme der Lichtstärke*. A change in brightness may have been incidentally produced, but this aspect of the stimulus was of no concern to him. He found that a decrease in intensity decreased the zone in which a color was sensed in its characteristic tone; he most assuredly does not claim, however, as Baird says he does that "the color limits were found to vary with changing brightness of stimulus" (see Baird, p. 17) in the sense in which Baird uses brightness, namely, as white-value. Klug[93] used a method somewhat similar to Abney's. He weakened a beam of light by interposing respectively one, two, and three thicknesses of ground glass, and found that the color limits were narrowed in each successive case. Thus he also made no attempt to isolate the effect of the brightness of the stimulus, and his work can not be cited as having any bearing on that problem. In Chodin's work, as we have already seen, the advisability of equating in brightness was discussed and decided against because of lack of evidence for the need of equating and because of the changes in color tone produced by changing the brightness of the colors. In giving Chodin as one of his authorities for equating, Baird refers to the passage in Chodin's article quoted in the original in this paper, pp. 44-45.

Baird writes: "Chodin remarks in his introduction: 'It is self-evident that in comparing the retinal sensitivity to different colors, the color stimuli employed must be of equal brightness and of equal saturation.' But this very essential condition was not fulfilled in his own experiments" (see Baird, p. 20). Baird has here again made a misinterpretation. The rather free translation of Chodin's statement: "Es bleibt nur übrig die Farben bei gleicher Sättigung und bei mittlerer Lichtintensität zu vergleichen"[94] and the failure to read carefully the discussion following it, are responsible, we presume, for the misinterpretation.

It is obvious from the foregoing résumé that the factor, bright-

[93] Klug, F. Ueber Farbenemfindung bei indirectem Sehen. A. f. O., 1875, XXI,,, pp. 274-278.

[94] Chodin, A. op. cit., p. 178.

ness of the stimulus, has been very inadequately treated in the literature. The specific question has never been answered, in fact has never really been investigated: Does the amount of brightness difference existing between the colors influence their limits of sensitivity in the peripheral retina? Aubert[95] and Chodin[96] and others have shown that the sensation limen of color when mixed with white is higher than the limen when mixed with black. This fact may be explained as due to the superior inhibitive power of white. But within what limits this greater inhibitive action of white is sufficient to cause the peripheral limit of a color mixed with white to be narrower than that of an equally intense color mixed with black has not been determined. And certainly it has never been shown that the brightness difference that exists between the standard colors at full saturation exerts an inhibitive action sufficiently strong to cause a change in the peripheral limits. It has never been claimed, for example, that a light color in its state of maximal saturation is more inhibited for sensation than a dark color in its state of maximal saturation by the brightness component inherent in each; in other words, that a saturated yellow is more inhibited by its brightness component than is a saturated blue by its brightness component. In fact, in strange contradiction to this, it has often been held that the colors which have the stronger white component are the more intense. Yellow, for example, has been frequently called a more intense color than blue just because of its proximity to white.

We must conclude, then, that the assumption that color limits must be investigated with stimuli of equal brightness is probably based upon the belief that stimuli differing in brightness differ also in intensity. This belief has doubtless arisen from the fact that as stimuli are ordinarily varied, a change of brightness is accompanied by a change of intensity, and conversely a change of intensity is accompanied by a change of brightness. But brightness and intensity are not inseparable variants. Conclusions should not be drawn, therefore, until the influence of bright-

[95] Aubert, H. Physiologische Optik, p. 532.
[96] Chodin, A. op. cit., p. 183.

ness change has been investigated in separation from intensity change. Since this investigation has not been made, we are forced to consider that the influence of the brightness of the stimulus upon the limits of color sensitivity is at present an open question, despite the verdict to the contrary by Bull, Hegg, Hess, and Baird. We have, therefore, included it in our own work as one of the points to be investigated. The results of this investigation are reported in the experimental section of this paper.

3. *Brightness of the Field Surrounding the Stimulus.*

The recognition of the influence exerted by the field surrounding the stimulus upon the limits of the color zones, has led to the substitution of the campimeter for the perimeter in investigations of the color sensitivity of the peripheral retina. The campimeter provides a means of readily changing the brightness of the field which surrounds the stimulus, so that the effects of these changes may be studied both upon the limens and limits of color and upon the quality changes that appear as the stimulus is carried from the fovea to the periphery.

The influence of the field surrounding the stimulus is twofold. In the first place, it directly modifies the stimulus by contrast induction, provided there is brightness opposition. This effect was observed and to some extent investigated by Aubert and Woinow before the campimeter came into use. In the second place, the campimeter screen, when of sufficient size, stimulates the entire retina uniformly and guarantees an equal brightness-adaptation of every portion. It was the recognition by Krükow[97] that former methods had allowed the retina to become unequally fatigued to chance objects in the surounding room, that led directly to the first use of the campimetrical method of working. Krükow did not, however, study the effect of different backgrounds. He used a uniform gray field to stimulate the surrounding retina, and mounted stimuli on cards of equal quality. In subsequent investigations, a black background was used almost exclusively. So far as induction is concerned,

[97] Krükow, loc. cit.

this screen gives conditions with the light-adapted retina somewhat similar to those existing in dark-room work; that is, in each case the stimuli are lightened by contrast from the surrounding dark field.

Woinow and Aubert worked only with small areas of background and thus secured the given brightness stimulation over but a small zone surrounding the part of the retina stimulated to color. Woinow[98] placed a disc made of black and white sectors behind the stimulus to be investigated. He found that, when the sectors were so adjusted that when rotated they formed a dark gray, the color limits were the same as when the sectors were arranged to give a light gray sensation. From these results, he concludes that the color zones are not influenced by the brightness of the field surrounding the stimulus. Aubert[99] fastened colored paper stimuli on white and on black cards. He found that the black card gave relatively wider limits for red; and that the white card gave relatively wider limits for yellow, green, and blue, except for very small stimuli.

The first campimeter described was apparently what is now called the Hering color-mixer.[100] Hess[101] was the first to employ it for an investigation of peripheral color sensitivity. He and later Tschermak[102] tested by means of it the influence of the brightness of the surrounding field upon the color limits. With this apparatus pigment stimuli are observed through an opening in a large gray screen, placed in the horizontal, which can be turned toward or away from the source of light, and in this way a surrounding field can be obtained that is lighter, darker, or equal in brightness to the stimulus at its point of disappearance as color. Hess and Tschermak both found that the limits of sensitivity to

[98] Woinow, M. loc. cit.

[99] Aubert, H. Physiologische Optik. pp. 541-543.

[100] Titchener in *Experimental Psychology, Instructor's Manual, Qualitative,* 1901, p. 20, ascribes the description of this apparatus to Hering, giving as reference A.f.O., 1889, XXV_4, p. 63. The writer is unable to find any mention of this apparatus in this or any other of Hering's articles. It is, however, described in some detail on p. 25 of the paper by Hess which just precedes and accompanies the Hering article to which Titchener refers.

[101] Hess, C. loc cit.

[102] Tschermak, A. op. cit., p. 561.

color were widest when the surrounding field was equal in brightness to the stimulus. If the stimulus appeared lighter or darker than the surrounding field, the limits were narrowed proportionately to the loss of saturation of the stimulus color due to the action upon it of the brightness quality induced by the background.

Fernald[103] used a vertical campimeter. She summarizes her results with white and black screens as follows: "All the colors except the reds are perceived at a greater angle of eccentricity with the dark than with the light backgrounds."

The only quantitative estimates of the effect of different backgrounds reported by these experimenters is given in terms of the effect upon the color limits. In no case has the amount of white or black induced by a given screen been determined, nor has the effect of the induction upon color sensitivity ever been tested in any part of the retina by the most direct means available, namely, the determination of the limen or threshold of sensation. Neither has any attempt been made to isolate the influence of the background from the influence of the brightness of whatever stimulates the retina immediately before the exposure of the stimulus. This factor, which we shall discuss under the name of *preëxposure,* is effective through the intensive brightness after-image that is set up on the retina and is superimposed upon the colored stimulus when it is exposed. Its importance has never been recognized by previous investigators, nor has its effect ever been studied in isolation from the effect of the brightness of the background. In short, in surveying the literature, one can scarcely help but feel that the study of the influence of the surrounding field has been neither analytic nor systematic.

4. *The General Illumination.*

The effect of the general illumination of the retina on color sensitivity has been recognized since the time of Purkinje and Aubert. It has been studied in some detail by a number of experimenters, among whom may be mentioned Kramer and Wolffberg. Both have shown that the sensation aroused by the colored stimulus is weakened by a reduction of the general

[103] Fernald, G. M. The Effect of Achromatic Conditions on the Color Phenomena of Peripheral Vision. Psychol. Rev. Monog., 1909, X, No. 42.

illumination, but neither, it may be mentioned, has given a method of keeping the general illumination constant. Kramer's[104] purpose was to determine the sensitivity of the eye under different intensities of daylight and artificial illumination. His method was as follows. Stimuli, 4 mm. square, of blue, yellow, red, and green paper on a black background were used. The distance at which the stimulus had to be placed from the observer to be just recognized as colored, was tested by sunlight and when the sky was obscured by clouds and for three intensities of each of the following sources of artificial illumination: candle light, gas, petroleum, sodium, potassium, strontium, and calcium lights. His results may be summarized as follows: (1) Red is seen at the greatest distance in all lights except calcium, in which case green is seen when farther away than red. The other colors are recognized in the order green, yellow, blue. (2) All the colors are recognized at a greater distance when seen by sunlight than when illuminated by artificial light or the dull light from a clouded sky. (3) As the intensity of the artificial illumination is decreased, the colors must be placed nearer the eye to be recognized. Kramer's method of working, however, may be criticized because he ignored the white contrast which the black background induced across the stimuli. The induction across the stimuli whose sizes were only 4 mm. square must have been considerable. It was, moreover, of different amounts in each case; because brightness contrast is greatest when there is maximal brightness opposition. The modification of the light colors, as a result of contrast induction, must, therefore, have been greater than that of the dark colors.

Wolffberg's[105] interest was in the influence of gradual alterations of the general illumination on the light and the color sensitivity of the central and of the peripheral retina. His room was illuminated by daylight entering through a window. Fifteen different degrees of illumination were produced by fastening from one to fifteen thicknesses of tissue-paper over the win-

[104] Kramer, J. Untersuchungen über die Abhängigkeit der Farbenempfindung von der Art und dem Grade der Beleuchtung. Inaug. Diss., Marburg, 1882.

[105] Wolffberg. Ueber die Prüfung des Lichtsinnes. A. f. O., 1887, XXXI., pp. 1-78.

dow. The illumination obtained when the window was uncovered was called 15/15; when covered with one thickness of tissue-paper, 14/15, etc. His method of determining the effect of variations of illumination upon the central retina was as follows: Pigment stimuli were placed at a standard distance of 5 meters from the observer, and the size of stimulus necessary to render it just visible in its true color was determined. In the peripheral retina, he investigated to what extent the limits of white and of colored stimuli were altered by reducing the illumination. In all his experiments, the stimuli were fastened on a black background. Wolffberg's results for the central retina are shown in the following table. The stimuli were circular in shape and of diameters given in columns 2, 3, 4, 5, and 6.

Illumination	Size of Red Stimulus	Size of Blue	Size of Green	Size of Yellow	Size of White
15/15	.5 mm.	3 mm.	3 mm.	1.5 mm.	.2 mm.
14/15	1.5	5	4	2	.5
13/15	2	6	6	4	1.
12/15	2.5	12	12	4.5	2
11/15	3	20	20	5	2.5
5/15	10	50	50	10	6

These results show that in the central retina a decrease of illumination has a greater effect upon the sensation of color than upon the sensation of white. Wolffberg next tested the effect of a gradual decrease of illumination upon the limits of sensitivity to white and to the colors. He found that the extent of the visual field was not narrowed for white when the illumination was decreased to 1/15. The color limits, however, narrowed gradually when the illumination was decreased from 15/15 to 3/15. The narrowing was in no case more than 15°. The relative extents of the fields remained unaltered, that is, the order of size was in every case blue, red, and green.

Although special investigations have been conducted by Kramer, Wolffberg and others to show the effect of changes in the general illumination upon color sensitivity, in general little if any precautions have been taken by earlier experimenters to prevent such changes when investigating color sensitivity. Either the experimenter has not considered the influence of the

general illumination, or he has been satisfied to take the rough precaution to work only on bright days at stated hours. Ole Bull,[106] for example, commented at length on the factor of general illumination, but suggested no method for its standardization. He writes: "The amount and nature of the general illumination are of more significance in perimetrical observations than one is accustomed to consider. It must always be noted whether the sky is clear or cloudy, whether it rains or snows. The extreme limits of the visual field for mixed light undergo such wide fluctuations that it is of little value to establish an average limit on the basis of a number of measurements. Changing illumination, conditioned by the time of day and of year during which the work is carried on, as well as the locality in which it is undertaken, produce variations in the same stimulus large enough to cause differences of from 10° to 20° [in the limit of sensitivity]. Especially in the nasal parts of the retina does the illumination influence the color limits, while their position remains more constant in the temporal retina." Fernald,[107] however, did make some attempt to obtain a standard illumination. She arranged white curtains at the windows of her optics-room which could be lowered on bright days and drawn on dark days. This rather crude method was used also by Thompson and Gordon.[108] It is scarcely necessary to point out that the method lacks the first essential of standardization, namely, a means of measuring.

It is surprising that Wolffberg as the logical corollary of his work, did not draw attention to the importance of standardizing the illumination of the visual field in all work on the color sensitivity of the retina, and show how it could be accomplished by a modification of his method of working. He already had at hand one of the essentials for standardizing, namely, a method of changing the illumination of his room. The other essential, a method of measurement by means of which an illumination could be identified with a previous illumination chosen as standard,

[106] Ole Bull. Perimetrie. Bonn, 1895, p. 8.

[107] Fernald, G. M. Psychol. Rev., 1905, XII, p. 392.

[108] Thompson and Gordon. A Study of After-images on the Peripheral Retina. Psychol. Rev., 1907, XIV, p. 122.

might have been derived from his results. For example, it would seem to have been a simple matter for him to have chosen as standard the particular illumination at which the red stimulus of 2.5 mm. diameter, the blue and green of 12 mm. each, the yellow of 4.5 mm., and the white of 2 mm. were just recognizable at a distance of 5 m. Stimuli of those sizes, it will be seen from the tables, were just recognizable at this distance at the illumination called 12/15, when 15/15 represents the illumination "bei günstige Tagesbeleuchtung." Using this condition as an index of the standard illumination, he could at any time have adjusted the illumination of the room by adding to or subtracting from the layers of tissue-paper covering the window, until the stimuli of these sizes were again just recognizable at the given distance. The accuracy and sensitivity of this method could have been tested by comparing the results of a series of determinations. An accurate and highly sensitive method sustaining some similarity in principle to the method suggested here, will be described by the writer in the experimental part of this paper.

The influence of changes in the intensity of the general illumination upon visual acuity has received some attention from physiologists and oculists. Although their work has no direct bearing on the influence of change of illumination upon color sensitivity, it may be of interest to note briefly their methods of dealing with these changes.

Schweigger[109] in 1876, using the Snellen series of optotypes and the formula $V = \frac{N}{n}$ in which *n* represents the distance of the test-object from the eye of the observer, and *N* the number of the series of the smallest of optotype series that can be recognized at that distance, found that on a clear day his visual acuity equalled 20/15, on a cloudy day it equalled 30/15. To correct for the errors in visual acuity introduced by changes in the illumination he first found the number of the series of the smallest optotypes that he himself could read at a given distance, then he determined this value for the patient at the same distance. Using his own results $V = \frac{N}{n}$ as standard, he determined the ratio of the patient's results $V = \frac{N^1}{n}$ to his own. This ratio $\frac{N^1}{N}$, he considers the expression of what the patient's visual acuity would be at standard illumination.

Cohn's and von Hoffman's interests lay mainly in testing the eyes of schoolchildren and in determining what was the lowest intensity of illumination of the schoolroom suitable for work. Cohn[110] in 1867 and 1883

[109] Schweigger, E. Sehproben. Berlin, 1876, Preface, pp. III-IV.

[110] Cohn, H. Untersuchungen der Augen von 10060 Schulkindern. Leipzig, 1876, p. 101; Hygiene of the Eye in Schools, translated by Turnbull, 1883, p. 131.

claims that as there is no photometer available for the measurement of the intensity of daylight, the eye must be its own photometer. Later in 1892[111] he states that L. Weber has made a daylight photometer, but as this apparatus is difficult of access, he would recommend apparently that the changes in visual acuity experienced by the eye with changes of illumination be used as a means of identifying a given degree of illumination. He endorses von Hoffman's[112] method of accomplishing this. According to this method, Type No. 30 of the Snellen optotypes is placed in the schoolroom 15 feet from the eyes of a child whose visual acuity is 15/15. If the child recognizes the letters of the test, the room is sufficiently well-lighted. Work in the room is to be suspended as soon as the child can no longer recognize the letters of the test. This provided a practical method, not for measuring the illumination of a room, but for detecting when a room has insufficient light for purposes of schoolwork.

Nicati[113] tested the influence of change of the intensity of artificial illumination upon visual acuity. His work was purely quantitative. He proposes a unit of measure by means of which to study this effect. This unit he calls *a photo*. *A photo* is the smallest intensity of light which when placed 1 meter from a test-object printed in black on a white card gives to normal monocular vision a normal acuity. The method of measuring the intensity of an illumination in *photos* is as follows. A source of light is brought towards the test-object until the observer has normal acuity. The intensity of the source then equals as many *photos* as the square of the distance of the light-source from the test-object, measured in meters. Nicati finds that there is an absolute logarithmic relation between visual acuity and intensity of illumination. As visual acuity is decreased in arithmetical series, intensity of illumination decreases in geometrical series. His table showing this relation is as follows:

Visual Acuity	1	.9	.8	.7	.6	.5	.4
Distance of source	1*M*		2*M*		4*M*		8*M*
Intensity in *photos*.	1	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{8}$	$\frac{1}{16}$	$\frac{1}{32}$	$\frac{1}{64}$

Since this relation exists, either the intensity of illumination can be con-considered a measure of visual acuity, or visual acuity can be considered a measure of the intensity of illumination. That is, the scale of visual acuity is a photometric scale and can be used as such. To measure the illumination of a room in *photos*, then, the visual acuity should be determined in different portions of the room, and the average of the *photos* corresponding to these values in the acuity scale be taken as the measure of the illumination of the room in *photos*. The method as formulated is apparently serviceable as a means of estimating the illumination of a room chiefly, if not entirely, when it is below what is needed for normal acuity of vision.

[111] Cohn, H. Lehrbuch der Hygiene des Auges. Wien und Leipzig, 1892, pp. 34-35.

[112] von Hoffman, H. Augenuntersuchungen in vier Wiesbadener Schulen. Klin. Monatsbl. f. Augenheilk., 1873, pp. 289-290.

[113] Nicati, W. Physiologie Oculaire humaine et comparée normale et pathologique. 1909, p. 163ff.

B. METHODS OF STANDARDIZING THESE FACTORS.

1. *Size of the Stimulus.*

No special method of standardizing the size of the stimulus is required. Each experimenter who has recognized it as a factor has chosen what he considered the most favorable area to work with, and has used that area in all of his comparative determinations. No limitations as to area have been prescribed other than that it must not be too large nor too small.

2. *Intensity of the Stimulus.*

As a general introduction to our discussion of the methods that have been used to standardize the influence of intensity, we wish to call attention once more to the fact that in no one of these investigations have the stimuli employed been equated with regard to the energy of the light given to the eye, nor have they been standardized in terms of any fixed unit of intensity that can be compared; and that until this is done, we have no proper means of determining the comparative limits of sensitivity to the different colors; nor of determining and expressing the comparative limen or j. n. d. of sensitivity. For example, attempts to determine the relative sensitivity of the retina to the four principal colors have been made among others by Aubert, Chodin, Raehlmann, Butz, Lam ansky, and Dobrowolsky: also by Bull, Hess, Hegg, and Baird. As stated above, however, these experimenters did not equate their stimuli with regard to the energy of light given to the eye for the investigations of the limits of sensitivity nor estimate sensitivity in terms of a common unit for the work on limens and j. n. d.'s of sensitivity. The last four, however, did attempt to equate in intensity, but the equation was made in terms of a subjective measure arbitrarily selected, namely, the proportion in which the pairs of antagonistic colors must be combined to produce gray, or, in terms of the Hering theory, to cancel each other.

At this point, two general criticisms may be passed on this method of equating. (*a*) The stimuli should not be equated in terms of any subjective measure if one is to test the comparative sensitivity of the retina to the different colors. This begs

the question at the outset. If, for example, a direct judgment of the intensity of the sensations aroused by two stimuli either at the limen or higher in the intensity scale be taken as the criterion for determining their equality, the method begins by making the stimuli of such physical intensity that they are sensed equally. In no fashion could the comparative sensitivity of the retina to the colors in question be determined by such stimuli. Suppose, for example, the limits of sensitivity of the peripheral retina were to be investigated, and for this, the stimuli which had been made subjectively equal for the central retina were used, the results obtained would not at all express the comparative limits for the colors in question. If these limits should be found to coincide, the conclusion could not be drawn either that the sensitivity of the retina to these colors extended only to this point, or that there was equal sensitivity at this point to the colors used. At most no more could be said than that approximately the same ratio of sensitivity to the two colors obtained in this region that was present at the point in the central retina for which they were equated; but this ratio may not be a 1:1 ratio. In fact, the investigator who gets his limits to coincide with stimuli so equated finds himself in the somewhat ludicrous position of having made his conditions such that the limits could not help but coincide, regardless of whether they actually ought to do so or not. He is not working with real limits, but with limits arbitrarily established, and the coincidence he finds is not a fact, at least not so far as he is able to determine by his method of working, but an artifact. To illustrate, the retina might be much more sensitive to red than to green; but if the red stimulus were reduced in physical intensity until the sensation it aroused was equal in intensity to the sensation aroused by the green, it is obvious that the comparative sensitivity to these colors could not be directly tested at any point. The limits of the red zone so determined might, for example, coincide with the limits of the green zone, although the extent of the red zone would have been much wider had stimuli of equal physical intensity been used. So much may be said for this as a type of subjective measure of equality, and what is said in criticism of its use for

investigating the comparative sensitivity of the retina has a general application to all subjective measures.

(b) The stimuli, especially should not be equated in terms of the cancelling power of antagonistic colors.[114] This method is analomous. One scarcely knows what it does accomplish. On the one hand, stimuli so equated are in no way equated in physical intensity; and on the other hand, it would be the merest assumption to say that they have equal power to arouse sensation. To demonstrate this, let us compare certain colors with regard to their comparative power to arouse sensation and to cancel each other. There are three ways by which we may judge the power of a color to arouse sensation:— (*a*) the value of its limen when mixed with a gray of equal brightness; (*b*) the value of its j. n. d. at different points in the intensity scale; and (*c*) the direct or introspective judgment of its intensity. Estimated in all of these ways, spectral red, as prepared in pigment colors by Maxwell after Helmholtz, has greater power to arouse sensation than the green of the series. And yet on the color-mixer, it requires 240° of this red to cancel or obliterate all trace of 120° of the green. And if sufficient blue be added to the mixture to give gray, the proportions of red and green are 165° and 115° respectively. Thus, whether the result of the combination is yellow or gray, the red stimulus, although it has the greater power to arouse sensation, is required to be in considerable excess of the green. We regret that we can not make a similar comparison for the blue and yellow of the Maxwell series, because we were unable to procure them in season for this work. But using the blue and the yellow of the Hering pigment papers, we find that this blue has a lower limen in a gray of its own brightness than the yellow has in a gray of its brightness, and that introspectively it is judged much more saturated than the yellow. And still at the general illumination we have chosen as our standard, 200° of blue are required to cancel 160° of yellow.[115]

[114] There are problems in the optics of color in which subjective equations of intensity may be desired. For a description of what the writer considers a proper method of making the subjective equation, see this paper p. 83, footnote.

[115] If the illumination is decreased, we find that a different proportion

In a later paper, we shall show that if the complementary colors can be assumed to cancel each other, because a certain amount of the one when combined with a certain amount of the other, kills it for sensation, then, by the same token, the non-complementary colors may be assumed to exercise a degree of this cancelling action. For a definite and considerable amount of each must be mixed with any other before it is sensed, the amount required varying over a wide range when one of them is combined with each of the others in turn. We may draw upon the non-complementary colors, then, for a further demonstration of our thesis that the cancelling power of colors upon each other is no measure of their power to arouse sensation. A notable instance of this is the combination of red and yellow to give orange. Working with the Hering pigments, we find that the standard orange of the series, judged as sensation, seems to be equally red and yellow. The standard red of the series, however, which is chosen to form the orange, has greater power to arouse sensation than the yellow by all of the tests mentioned above. Still 295° of red are required to be combined with 65° of the yellow to give the orange which as we have said is equally red and yellow as sensation. Orange furnishes us with only one instance of the non-equivalence of cancelling power to sensation-arousing power that may be found among the combinations of non-complementary colors.[116]

We must, then, conclude that even if one were to err so profoundly as to choose a subjective measure for equating the intensity of his stimuli for an investigation of the comparative

is required to produce cancellation. This difference depends upon the fact that colors do not lose their saturation with equal rapidity with decrease of illumination. The dependence of cancelling proportions upon the general illumination may be pointed out as a minor source of error in the use that has been made of this method by investigators who have conducted their experiments in daylight, for they did not work at an invariable or standard illumination.

[116] In the above demonstration that cancelling power can not be taken as the equivalent of sensation-arousing power, we have assumed that we have not left our work open to criticism in the use of pigment instead of spectral colors, or even in passing from one series of pigment colors to another, because in each case, our test of the cancelling power and of the sensation-arousing power was made with the same stimuli.

sensitivity of the retina to the different colors, this measure should not be selected in preference to the power to arouse sensation as determined either by limen tests, by direct introspective judgments of intensities, nor by the j. n. d. method described on p. 83 footnote. One can only surmise the following reasons for the selection. (*a*) The limen and the just noticeable difference tests, either of which is a proper method of estimating the power of a stimulus to arouse sensation, were probably not taken into consideration at all. The alternative test, the introspective judgment of equal intensities, is difficult to make. And the method given on p. 83 footnote, which is preferable to any method known to the writer for subjectively equating stimuli of all degrees of intensity, has never been suggested even in principle prior to the publication of this paper. It may have been thought that equality based on cancelling power could be substituted for the equality as determined by the other methods.

The reason for selection of equation in terms of cancelling power is not stated by any one of the four men who has made this selection. Considering the statement of each in turn, we find that Bull who wished to obtain color stimuli of equal saturation and brightness, merely states that he does this by establishing pairs of colors such that equal amounts of each cancel and give a gray that conforms to the standard gray he has chosen (A. f. O., 1881, XXVII., p. 95). Hess, aiming to obtain a red light such that its red *Valenz,* or, as he says, its capacity to arouse red sensation, is equal to the green *Valenz* of a green light, writes: "Als Nächstliegende erscheint es nun, einem roth- und einem grün-wirkenden Pigmente den gleichen Roth und Grünwerthe dann zuzuschreiben, wenn dieselben zu gleichen Theilen eine farblose Mischung geben" (A. f O., 1889, XXXV., p. 39). Hegg wishing to equalize the color-values of his stimuli, claims that this is possible for only the two members of each pair of antagonistic colors. Red can be made equal in color-value to green, he says, or yellow to blue, but green and blue can not be equalized. He continues: "Wir betrachten ein *Roth* und ein *Grün* als chromatisch äquivalent, wenn sie auf der Rotationsscheibe zu gleichen Theilen gemischt sich gegenseitig total aufheben, so dass eine Mischung entsteht, welche weder ins rothliche noch grünliche sticht." (A. f. O., 1892, XXXVIII., p. 149). Baird offers no reason whatever for selecting the method of cancelling power by means of which to equate color-values. He apparently takes for granted that this method is the only one, and does no more than describe how the method was applied to his particular stimuli.

The search for a reason for this selection may, however, be pushed back a little further. We find that in 1880 before any of the work mentioned above was published, Hering (Lotos. Jahrbuch für Naturwissenschaft,

1880, I, pp. 76-107) had made statements from which we can conclude that in his opinion two antagonistic colors of equal sensation-arousing power cancel. Hering's statements leading to this conclusion are as follows: (*a*) 'Die Vermögen der Lichtstrahlen, die weisse Empfindung zu fördern, will ich die weisse Valenz der Lichtstrahlen nenne." (p. 79.) (While this definition is not specifically repeated for colored light, still it is obvious from the text that it applies to colored as well as to white light).[117]

[117] The following quotations are appended to show the use of *Valenz* by Hering and Hess:

Hering (Zur Erklärung der Farbenblindheit aus der Theorie der Gegenfarben. Lotos—Jahrbuch für Naturwissenschaft, 1880, I., p. 76-107) writes (p. 79): "Die Vermögen der Lichtstrahlen, die weisse Empfindung zu fördern, will ich die weisse Valenz der Lichtstrahlen nennen.

"Die Grösse dieser Valenz ist offenbar von zwei Factoren abhängig: ersten von der objectiven Intensität oder lebendigen Kraft, mit welchen die Strahlen verschiedener Wellenlänge bis zur empfindlichen Netzhautschicht gelangen, und zweitens von dem, was wir die specifische weisse Erregbarkeit des Sehorgans gegenüber den Strahlen verschiedenen Wellenlänge nennen, d.i. das Vermögen dieses Organs, unter dem Einflusse jener Strahlen die Weissempfindung deutlicher werden lassen.

"Ausser der weissen Valenz, welche allen Lichtstrahlen gemeinsam ist, kommen nun den einzelnen Strahlenarten verschiedene farbige Valenzen zu. Allen Strahlen vom aussersten Roth oder vom Anfange des Spectrums bis zu jenem im Tone reinen Grün, welches eine Gründfarbe ist und welches wir das Urgrün nennen wollen, haben eine gelbe, allen Strahlen vom Urgrün bis zum violetten Ende des Spectrums eine blaue Valenz."

Hess (Ueber den Farbensinn bei indirectem Sehen, A. f. O., 1889, XXXV., pp. 1-60.) writes (p. 30): "Unter weisser Valenz eines farbigen homogenen oder zusammengesetzten Lichtes versteht Hering den Helligkeitswerth desselben für eine Netzhautstelle, welche das farbige Licht wegen mangelhaften Farbensinnes oder aus anderen Gründen farblos sieht" (p. 39): "Um über das gegenseitige Verhältniss der Abnahme der Empfindungsvermögens für Roth und Grün, resp. Blau und Gelb überhaupt Untersuchungen anstellen zu können, ist es zunächst erförderlich, für beide Arten des Empfindungsvermögens ein gemeinsames Maass zu finden. Verschiedene grüne Lichter besitzten die Fähigkeit, grüne Empfindung zu erzeugen, in sehr verschiedenem Maasse, sie sind, um es kurz zu bezeichnen, sehr verschieden grünwirkend. Das mehr oder minder grosse Vermögen eines Lichtes, grün zu wirken, bezeichnen wir mit Hering als die grüne Valenz oder den Grünwerth des bezüglichen Lichtes". (p. 40): "Bestimmen und messen lässt sich derselbe nur in Bezug auf ein als Normalgrün gewahltes Pigment, welches unter genau denselben Beleuchtungsverhältnissen wie das zu untersuchende gesehen wird. Ganz analoges gilt von dem Roth-, Gelb-, und Blauwerthe eines Pigmentes.

"Für die vorliegende Frage handelt es sich aber nicht bloss darum die Grünwerthe oder die Rothwerthe verschiedenen Pigmente je unter sich zu vergleichen, sondern den Grünwerthe eines grünwirkenden mit dem Rothwerthe eines rothwirkenden Pigmentes.

"Als das Nächstliegende erscheint es nun, einem roth- und einem grünwirken-

(*b*) "Zwei homogenen Lichter, nun, von welchen das eine ebenso gelb (oder roth) wirkt, und das andere blau (oder grün) so dass beide Valenzen sich aufheben, nenne ich gegenfarbig äquivalent" (pp. 83-84). In the first of these statements he directly calls the capacity of a color to arouse sensation its *Valenz*. And from the second it may readily be derived that when the yellow-sense, for example, is affected as strongly by yellow light as the blue-sense is affected by blue light, complete cancellation will ensue,—that is, equality in cancelling power may be considered as the equivalent of equality in capacity to arouse sensation. In making this deduction we have of course assumed that *wirkt* refers to sensation-arousing action and not to cancelling action. We have no doubt that this assumption is correct, still it may be worth while to bring forward direct evidence in support of this point from a statement made by Hess while working under Hering's direction. Hess writes: "Das mehr oder minder grosse Vermögen eines Lichtes grün zu wirken, bezeichnen wir mit Hering als die grüne Valenz oder den Grünwerth des bezüglichen Lichtes" (op. cit., p. 39). Here *Vermögen grün zu wirken* is made the equivalent of *Valenz* and *Valenz* by definition is the capacity of a color to arouse sensation. Hence we have little hesitation in assuming that in the case in question *wirkt* also refers to the sensation-arousing action of the colored light and not to its cancelling action, and in concluding, therefore, that Hering believed that antagonistic colors of equal power to arouse sensation would also have equal power to cancel each other. Since this is true, it is probable that the followers of Hering (Hess and Hegg) assumed the equivalence of power to arouse sensation and power to cancel and equated their stimuli accordingly. That Hess was actuated by some such reason is shown by a statement made by him in his discussion of this point. He writes: Die von Herrn Professor Hering angegebene, oben geschriebene Untersuchungsweise gestattet mit grosse Genauigkeit den zu vergleichenden Pigmenten gleich grosse farbige und gleich grosse weisse Valenz zu geben, sie ermöglicht es, für die Werthigkeit der Farben einen genauen numerischen Ausdruck zu winnen und in die Rechnung einzuführen" (op. cit., p. 58). Hegg also seems to refer back to Hering, for he uses the Hering terminology in discussing the equation of his stimuli.

Or (*b*) since cancellation is the corollary to the assumption of an assimilation-dissimilation mechanism, it may have been considered for some reason, not readily understood by the writer, that an equation based upon it is the proper one to make.

Having said this much about the impropriety of selecting a subjective measure for the intensity equation of stimuli, let us

den Pigmente den gleichen Roth-und Grünwerth dann zuzuschreiben, wenn dieselben zu gleichen Theilen, z.B. auf dem Kreisel gemischt eine farblose Mischung geben, im Falle sie dazu aber in einem anderen Verhältnisse gemischt werden müssen, anzunehmen, dass sich der Rothwerthe des einen zum Grünwerthe des anderen umgekehrt verhält wie die Grösse der beiden zur Herstellung einer farbosen Mischung nöthigen Sectoren."

pass to a résumé of the attempts that have been made to apply this measure by Bull, Hess, Hegg, and Baird. Hegg selected four stimuli that suffered no alteration of color tone in passing from the center to the periphery.[118] These were a bluish-red, a bluish-green, a blue, and a yellow. They were equated in pairs, the bluish-red to the bluish-green, and the blue to the yellow, as follows. It was determined in what proportions the members of each pair had to be combined to produce gray, and from these proportions, values of the sectors of the stimulus disc were calculated for each color. The procedures of Bull and Hess were essentially similar..

Baird, employing the light transmitted by gelatines, prepared blue, yellow, red, and green stimuli as follows. A lantern containing an incandescent lamp of 16 candle-power was used as source of light. The stimulus light was emitted from the lantern through a circular aperture, 15 mm. in diameter. Gelatines were placed over the aperture in combinations which gave the four stable colors, and their spectral values were obtained. A disc in which two windows of equal size had been cut, was rotated on a motor in front of the lantern. The combination of gelatines to give the red stimulus was fastened across one of the windows, while the green combination was used to cover the other window. As the windows were of equal size, the rotation of the disc gave a mixture which contained equal proportions of both stimuli. The gelatine combinations were changed by adding, subtracting, or substituting until the mixture showed no trace of color. Similar equations were obtained for the blue and the yellow stimuli.

It will be seen from the work of these men that even if their methods had been based upon a proper principle of equating, they would not be adequate for all that is involved in the problem

[118] Only one meridian was used for determining this invariability of color tone. It is obvious that a conclusion should not be drawn from such a scant investigation of the sensitivity of the retina. For example, working with the red, green, blue, and yellow of the Hering standard papers, the writer has found that with a careful standardization of factors, an investigation in any considerable number of meridians shows that stability of tone is possessed by the blue alone.

of determining the comparative sensitivity of the retina to the different colors. For not only is the comparative sensitivity to the complementary colors desired, but to the non-complementary colors as well. The method offers no possibility, for example, of equating red and green to blue and yellow. One can only conjecture how much of our present conception of the comparative extent of the different zones of color sensitivity is an artifact due to the use of stimuli that have not been equated with reference to the energy of the light-waves they give to the eye. In addition, then, to the objection that the methods that have been used thus far to equate the color stimuli in intensity are found to be essentially wrong in principle, the further criticism may be offered that they are not adequate in scope. An energy equation of the light-waves by means of some radiometric device, for example, the thermopile, the bolometer, the selenium cell, or what not, alone seems adequate to the requirements set by the problem of determining the comparative sensitivity of the retina to the different colors, or the comparative limits of the zones of sensitivity.

Energy equations in terms of radiometric units have been made by Langley and Pfund, but up to this time no investigation of color sensitivity has been made with colors equalized in energy. Langley[119] invented the bolometer and determined by means of it the relative distribution of energy in the normal spectrum. In order to equalize the energy of the different colors, he states that one may vary the width of the collimator-slit until equal radiometric readings are obtained. In his own experiments on visual acuity, he does not, however, proceed in this way. Tables of logarithms were illuminated in a dark-room by monochromatic light representing known amounts of energy. The greatest distance at which the figures could be read was determined for each of the colors, and corrections were applied for inequalities in the energy of the different lights. The corrections were made in terms of the distribution obtaining in the following table.

Pfund used the first method suggested by Langley. In an

[119] Langley. Energy and Vision. Amer. Journ of Science, 1888, XXXVI., 3rd Ser., pp. 359-379.

investigation of the changes in the resistance of selenium to lights of varying wave-length, he employed differently colored

Wave-length	μ .35	μ .38	μ .45	μ. 50	μ .55	μ .60	μ .65	μ .70	μ .75	μ .768
Heat	1.8	5.3	11.9	17.3	20.7	21.9	22.2	21.4	20.7	20.2

beams of equal intensity. The intensity equations were made as follows. Using first a Rubens thermopile[120] and later a radiomicrometer,[121] Pfund determined which wave-length gave the least galvanometer deflection. He then reduced the more intense beams by interposing a smoked wedge of the proper thickness until every portion of the spectrum produced the same deflection. In this way he obtained colored lights of known and constant energy.

Psychological investigators have been slow to recognize the importance of standardization of intensity in radiometric terms of the colors which are to be used for the investigation of sensitivity. The only equations of intensity have been made in subjective terms, a procedure which if done by a proper method may be legitimate for work on certain points relative to existing color theories, but which is not adequate (see this paper, pp. 64-65) to meet the requirements of the problems which deal with the comparative sensitivity of the retina to the different colors.

Note.—Since the completion of this paper, the report of Watson and Yerkes concerning methods of studying vision in animals has been published (Behavior Monographs, 1911, I, pp. 1-89). For the measurement of the intensity of the stimulus they find two methods available, photometry and radiometry. They write: "The method of photometry in all its forms is dependent upon the visual capacity, training, and the special skill of the observer who attempts to use it. For this reason, and others only less important, it is usually desirable to supplement photometric measurements of photic stimuli by measurements of their value in terms of energy. Hence the pertinence of physical measurements. Determination of the value of photic stimuli in terms of heat units by radiometric procedure has proved feasible. Radiometry yields a measurement which is relatively independent of the visual peculiarities of the observer, and it therefore supplements in an invaluable manner the results of photometry" (p. 11).

The authors in question then decide in favor of radiometric measurement

[120] Pfund, A. A Study of the Selenium Cell. Philos. Mag., 1904, VII, Ser. 6, p. 26.

[121] Pfund, A. The Electrical and Optical Properties of Metallic Selenium. Phys. Rev., 1909, XXVIII, p. 326.

and control of the stimuli to be used in determining the animal's color sense. Their reasons for this decision are not, however, those stated in the above criticism of subjective methods of equation either by cancelling power or by sensation-arousing power, namely, that these methods are essentially wrong in principle for tests for the comparative sensitivity of the eye to different colors. That they do not consider them wrong in principle for work of this kind is shown in fact by their recommendation of the Hegg colored papers. The colors of the Hegg papers are equated in intensity in terms of the cancelling power of the complementary colors, the worst of the subjective methods discussed. They write: "These [the Hegg papers] are mixtures of oils on paper yielding the hues red, yellow, green, and blue. These hues are claimed to be equal in intensity and saturation for the human eye. The set is useful as a means of ascertaining, in a preliminary survey, whether an animal readily discriminates two hues which for us are of nearly the same intensity and saturation" (p. 32). It is obvious also that they do not consider the photometric method of equating intensities (also a subjective method) wrong in principle. The method is not recommended merely because it depends upon the visual capacity, training, and special skill of the observer. But the fact that they endorse this method to supplement the radiometric procedure or rather, as quoted above, the radiometric to supplement the photometric shows that they do not realize the absolute diversity of the photometric and of the radiometric curve. Their conclusion, then, in favor of the method of radiometry for measuring the intensity of the stimulus is based upon very different arguments from those which have governed the similar decision reached in the above discussion. They do not seem to entertain any criticism of the subjective method of equating, either the method which measures cancelling power, or the method of photometry, nor do they recommend that either be discarded. Their choice of energy measurement is due largely to the fact that they wish a method which is as free as possible from subjective errors.

3. *Brightness of the Stimulus*

The same investigators who sought to obtain stimuli of equal intensity, attempted also to equate these stimuli in brightness. This may be done in two ways: the white-values of the colors as they appear in direct vision may be equated, or the white-values as they appear in indirect vision may be equalized. The first method was used by Bull who made direct comparison judgments of the relative brightness of the colors, facilitating his comparisons by the use of intermediate color-tones. For example, a blue was changed in brightness until it appeared as light as a given blue-green. Green was then made equal to the blue-green; yellow-green to the green; yellow, to the yellow-green, etc. Hess, Hegg, and Baird employed the second

method. The stimuli were carried to a point in the field of the peripheral retina at which they appeared colorless and their brightness values were altered until the gray sensations obtained from all the stimuli were equal.

Hegg, who used pigment colors, observed the stimulus through an opening in a gray screen, whose brightness could be altered by turning it toward or away from the source of light. He adjusted the screen so that its brightness was the same as that of the gray sensation aroused by the green stimulus in the peripheral retina. Retaining this setting of the screen, he replaced the green by the red stimulus, the intensity of which he had previously equated to the intensity of the green by the method described and criticised in the preceding section. The red stimulus, which was composed of 216° of red, 55° of blue, 89° of white, when observed in the extreme periphery, was seen as a gray that was lighter than the screen. To make the stimulus and the screen of equal brightness, 5° of the white sector had to be replaced by black. A complication arose when blue and yellow were equated to this brightness, resulting from the changes in color-tone which took place. Hegg found that when he added white to lighten the blue stimulus, a sensation of reddish-blue was aroused. (Chodin, it will be remembered (see p. 45), saw in this fact an argument against the possibility of equating the brightness of colors for investigations of this kind.) To cancel this effect, he added green. The addition of black to yellow, which was necessary in order to equate the brightness of yellow to green, resulted in a greenish-yellow sensation. To this he added red in a sufficient amount to cancel the greenish appearance of the fusion.[122]

[122] In connection with a study (done in cooperation with Dr. C. E. Ferree) to determine the physiological level at which the fusion of colored with colorless light sensation takes place, the writer attempted to add sufficient red to cancel the green in a mixture of yellow and black. A curious paradox was observed. Starting with 55° of yellow, and 305° of black, and keeping these proportions relatively constant while red was being added to the mixture, it was reported by a number of observers that, after the addition of about 10° of red, it was seen in the mixture with the green. As more was added, the green and red continued together in varying proportions, until, with about 45° of red in the mixture, it dominated the fusion, which was seen as a dark brownish-orange. Our ob-

Hegg does not give the proportions of the final white-green-blue *Urblau* and the black-red-yellow *Urgelb* which, he claims, were equal in brightness to the *Urroth* and *Urgrün*.

Baird also used the method of indirect vision comparison. The two stimuli to be equated were placed one above the other at a point at which both appeared colorless in the periphery of the retina. The brightness of blue was chosen as standard, and the red, green, and yellow stimuli were darkened to equal it by rotating an episcotister in front of each of them in turn. The sectors of the episcotister were adjusted so that each stimulus was darkened as much as necessary to cause the colorless sensation aroused by it in the periphery to be the same as was aroused by the blue stimulus. Baird does not say that his work was complicated by changes in color-tone. His method would at first glance seem to be more simple than that of Hegg. When, however, we remember that the equation of brightness and apparent intensity had to be carried on hand in hand, we see some of the difficulties he must have encountered. His problem, was to bring the complementary colors to such intensity, that 180° of one cancelled 180° of the other; and at the same time, to maintain them all of the brightness of the blue. But it is apparent that by his method of equating in brightness, an alteration in the amount of colored light coming to the eye is produced every time a change in brightness is made. And as the brightness of the several stimuli had to be changed by unequal amounts to bring them all to the brightness of blue, the amount of colored light coming to the eye was also changed by unequal amounts. This much of the procedure is sufficient to show the difficulty that confronts the experimenter. To equate either for brightness or cancelling power, disturbs the equation established for the other; that is, when the stimuli are brought to equal brightness, their cancelling power will no longer be equal, and *vice versa*. It is obvious that

servation has been verified too many times and by too many observers for us to question its validity. It stands, then, in direct contradiction to Hegg's claim that a change in color-tone produced by altering the white-value of a color can be remedied by adding the complementary color to the stimulus. The difficulty then, seems insurmountable, and stands as one of the objections to the attempt to equate colors in brightness.

the goal desired, if it can be attained at all, must be reached by a series of approximations; and that in the end the experimenter will have very much altered stimuli. Since to equate for both at once, involves making much more radical changes in the stimuli than to equate for one alone, it is plain that in doing both, we but add to the objections we have already made when each is done alone.

It is to be deplored that Baird does not tell us just how he worked in this most difficult part of his technique. The defect is serious, for as the report of his method stands, one can neither pass judgment on its adequacy, nor be sufficiently guided by it, should one attempt to repeat the work. Of the technique that is described, however, the following criticism may be offered. In the equation of the brightness of two stimuli, Baird carried them to an angle of excentricity, at which both appeared colorless. Now, it is seen from his tables, that the limit of blue is some 15° wider than that of green. He has, then, either to show that the brightness of green is the same at its limit as it is 15° peripheralwards, or to equate the brightness of the colors at their individual limits by some means, such as the flicker method.

Since Bull equated his stimuli by the direct vision method, and Hess, Hegg, and Baird by the indirect vision method, a word may be said in concluding this topic with regard to which is the proper method. Obviously, the decision rests upon whether or not the colors have different relative white-values at center and periphery. That they do has been reported among others by Tschermak,[123] and we have been able to confirm this statement. The equation should, therefore, be made in the peripheral retina. As we shall show in the experimental section of our paper, however, no equation should have been made by any of these men for the work they were doing, because unless the stimuli used are extremely weak in saturation, to equate in brightness for the investigation of the limits of sensitivity not only is unnecessary, but results in positive harm. If, however, in other work in the peripheral retina the need for equating should arise, the writer would urge not only that the equation should be made in the

[123] Tschermak, A. op. cit., pp. 564-575.

peripheral retina, but that it should be obtained at the point at which the investigation is to be made.

c. Summary.

With regard to the attempts that have been made to standardize, the results of our historical survey are found to be largely destructive in character. They show, however, that a decided need for standardizing has been recognized. This in itself was a first step in the right direction. The following factors have been discussed: (*a*) *The size of the stimulus.* This factor has been the most adequately treated by previous investigators. Its influence as a factor has been shown, and with it the need of careful measurement of the actual size of the stimulus and of its apparent size as determined by its distance from the eye of the observer. There is still need, however, for further work. While it has been generally held that an increase in the area of the stimulus functions in some degree as the equivalent of an increase in intensity, and thus influences the limits and limens of color sensitivity, no quantitative estimate has been made of the degree of this equivalence. Exact knowledge of this point is not only of general interest in psychological optics, but it is needed in turn in certain problems of standardizing. For example, it is often required that the size of the stimulus be varied and its intensity for sensation be kept constant. This can be done only when the ratio of equivalence is known. As stated on p. 6, this ratio is now being worked out in this laboratory. The results will be reported later.

(*b*) *The intensity of the stimulus.* The influence of the intensity of the stimulus upon color limens and color limits has been pointed out, but no adequate standard of measure has been employed. In dealing with the comparative sensitivity of the retina to the different colors, estimated in terms of the limits, it is obvious that equal amounts of light should be used. Estimated in terms of the limens, the amounts used should be determined in terms of units that can be compared. The problem of the measurement of these amounts of light is wholly physical, hence the standard of the physicist should be adopted. The determination should be in terms of energy as measured by the bolometer,

the thermopile, or other radiometric device. Only in this way so far as we know, can the retina's sensitivity to the different colored lights be obtained in terms of units that can be compared.

(*c*) *The brightness of the stimulus.* Brightness and intensity have been much confused in the literature of the subject. The effect obtained by varying both factors has often been attributed to change in brightness alone. The effect of change in brightness has never been investigated in isolation. This factor, then, occupies the novel position of having been standardized for work on the limits of color sensitivity before the need for such control has been shown.

(*d*) *The preëxposure.* Only in a very general way has the effect of the brightness of the preëxposure been recognized, and the precise reason for its influence has been very little understood. No quantitative estimate of the effect has been made, and no attempt at standardization has been undertaken which has shown any comprehensive knowledge of how the factor works.

(*e*) *The field surrounding the stimulus.* Considerable attention has been given to this factor. A small amount of qualitative work has been done, and some attempts have been made to secure control of the factor. More detailed knowledge, however, is needed of its influence, quantitative and qualitative, over a wider range of the retina. Especially should its relation to general illumination be studied. Until this relation is understood and some means is taken to render the general illumination constant, no effective estimation of the influence of the brightness of the surrounding field can be obtained, nor can it be eliminated as a factor from the color observation.

(*f*) *The general illumination.* The influence of the illumination of the visual field on color sensitivity has been recognized and rough attempts have been made to determine the amount of this influence. The different ways in which changes in general illumination affect color sensitivity have not, however, been determined, and the relative importance of each has not been estimated. Very little attempt at standardization has been made because the first essential of standardization, namely, a sensitive means of measurement, has not been had.

III. EXPERIMENTAL.

A. Purpose of Investigation.

The purpose of this investigation includes the following points. (1) The color observation will be analyzed for the brightness factors that influence its results. (2) A systematic study will be made of these factors with special reference to the determination of their effect upon the color sensitivity of the retina and upon the limits of sensitivity to different colors. (3) It will be ascertained whether the effect of these factors can not be explained in terms of the action of brightness upon color in the peripheral retina and of the rapidity with which the sensitivity to color decreases from the fovea outwards. (4) Methods will be devised to standardize these factors in so far as our results show the need of standardization. No attempt will be made at this point to study the factors that pertain to the source of light with the following exception. Brightness will be isolated from intensity and the effect on the limits of sensitivity of changes in the brightness of the stimulus, made without altering the amount of colored light coming to the eye, will be determined in order to find out whether or not colors should be equated in brightness when the limits of sensitivity are investigated. Moreover, since our problem is concerned only with the brightness factors that influence the action of the colored stimulus upon the retina, the writer will not feel obliged to concern herself with the standardization of her stimulus with regard to either quality or intensity any further than is needed to show the effect of the brightness factors upon the retina's response to these stimuli. All the standardization that is needed will be accomplished by using the same stimulus for all observations the results of which are to be compared; that is, no comparisons will be made except of the effect of the different brightness factors upon the same stimulus. For obtaining results so purely comparative the standardization afforded by pigment papers should be adequate, provided a standard illumination can be obtained so that the amount of

colored light reflected from the pigments will be constant from test to test. Since we were able to secure a highly sensitive means of duplicating our illumination from observation to observation, the standardization of the stimulus afforded by the Hering pigment papers has been considered adequate. More especially has this degree of standardization been considered adequate because the results are to be used primarily merely as a guide in the formulation of a method of working. Having secured a method of working, however, that will permit of a close duplication of results from observation to observation with the pigment papers, the writer will attempt to adapt the method to work in which the colors of the spectrum are used. In order to do this, the following requirements will have to be met. (1) A spectroscope will have to be devised by means of which the retina can be stimulated at any degree of excentricity in any meridian that is desired, for example, a spectroscope that can be used in conjunction with the rotary campimeter[1] in all its adjustments. Such a spectroscope having all the freedom of movements of its parts needed for use with the rotary campimeter has been devised in this laboratory and is now under construction. (2) In order that the stimulus-opening in our campimeter be filled with light sufficiently homogeneous for our purpose, a prism of high dispersive power will have to be procured for use in our spectroscope. A compound prism of the Cassie type[2] seems adequate for this requirement. Such a prism constructed to our special order is now being made for us in Germany. (3) In order that the light may undergo high dispersion and still be sufficiently intense for work in a room lighted to the degree that some phases of our problem demand, a source of light of high intrinsic brilliancy is needed. Constancy in candle-power should also be had. A high voltage Nernst filament seasoned for 100 hours or more and operated on a steady circuit will give, the writer believes, the intensity and constancy required.

Having completed our work of standardizing the factors extraneous to the source of light, an attempt will next be made

[1] For a description of the rotary campimeter see this paper p. 87 ff.
[2] Cassie. Philos. Mag., 1902, III. Ser 6., p. 449.

to secure a better control of the source. Standardization up to the present can be considered successful only with regard to the quality of light. No adequate work has been done on the standardization of the quantity of light for work on color sensitivity. As stated earlier in the paper, the writer believes that this can be done only by means of energy determinations. She expects to do her radiometric work by means of a surface thermopile (Coblentz model)[3] and a DuBois-Rubens *Panzergalvanometer,* unless future results show that some other combination of radiometer and galvanometer is more satisfactory.

Finally from the work of standardization it is our hope to return to the investigation of the problems which we were in the beginning forced to abandon because the work could not be satisfactorily done by the methods now in use in the optics of color. A brief statement of the plan of our future work has already been given in an article published in conjunction with Dr. Ferree in the American Journal of Psychology.[4] In order that the scope of this work be known at this point, and that the importance of the present investigation be understood in relation to this work, the statement is appended here.

"About a year ago[5] the writers undertook to determine the retina's sensitivity, relative and absolute, to colored light in terms of units that can be compared. Since several years will be required to complete this work, they have thought it best to publish a preliminary note showing briefly the purpose and scope of the investigation. The following points will serve to indicate what is being attempted in this study.

"(1) All measurements of sensitivity will be made in radiometric terms. This will give an expression of the sensitivity of the retina in units which are directly comparable with one another. At present we have no direct estimate of the comparative sensitivity of the retina to the different colors further than is ex-

[3] Coblentz, W. W. Instruments and Methods Used in Radiometry. Reprint No. 188, Bulletin of the Bureau of Standards, 1911, IX., pp. 22-23.

[4] Ferree, C. E. and Rand, G. A note on the Determination of the Retina's Sensitivity to Colored Light in Terms of Radiometric Units. Amer. Journ. of Psychol., 1912, XXIII, pp. 328-332.

[5] The first public statement of our intention to use radiometric units in the investigation of the retina's sensitivity to color was made to the committee in charge of the Sarah Berliner Research Fellowship, February 1, 1911.

pressed, for example, by the relative width of the collimator-slit that has to be used to arouse color sensation when a light-source of a given candle-power is used. This kind of comparison is obviously unfair because such different amounts of energy are represented from point to point in the spectrum that a given width of slit would admit many times the amount of energy at one part of the spectrum that it would at another. In short, no adequate estimation and expression of the retina's sensitivity to color, comparative or absolute, can be made by means of the methods now in common use.[6]

"(2) Comparisons of results on many other points with such disparate stimuli seem equally inadequate: the relative time required for the different color sensations to attain their

[6] Two criticisms have been received from private sources which it may be well to take account of here. In one the possibility of a point of view is implied, in the other a point of view is stated. The point of view, the possibilty of which is implied in the first criticism, is that it is not proper to estimate the sensitivity of the retina in terms of physical units, because it is generally conceded by modern investigators of color vision that the retinal processes which transform the physical energy of the color stimulus into nervous energy is essentially chemical in its nature; and one can not assume that a certain amount of physical energy arouses an equal amount of chemical energy in the retina, nor that equal amounts of physical energy arouse equal amounts of chemical energy. In answer to this, the writers would point out that these chemical substances are a part of the retina and their respective inertiae constitute one set of factors that determine the sensitivity of the retina to the different colored lights. It is not necessary to assume, therefore, that a given amount of physical energy arouses an equal amount of chemical energy, etc., in order to make our determinations of the comparative sensitivity of the retina to the different colors in terms of physical units. That would be necessary only if we were trying to separate out the nerve filaments, and to measure or compare their sensitivity to the different colors in terms of physical units. But even in chemical theories when speaking of the comparative sensitivity of the retina to the different colors, we do not mean the comparative sensitivity of the nerve filaments alone. We include the reaction of the chemical substances as well. Our contention, then, is that if the determination of the comparative sensitivity of the retina to the different colors is a proper problem, the determination should be made in terms of quantities that can be compared. This can be done either (*a*) by using lights equalized in energy and determining by means of a sectored disc the relative amounts of these lights that are required to arouse sensation; or (*b*) by using lights representing different amounts of energy and measuring directly in terms of radiometric units the amounts required to arouse sensation. We scarcely need point out that in speaking of the comparative sensitivity of the retina to the different colors we are not raising a new problem, but are merely recognizing a very old one.

The second criticism is in substance that a quantitative comparison of the effect of the different wave-lengths on the retina is improper because the different wave-lengths constitute stimuli too different in kind to permit such comparison. This criticism we leave open, because we do not wish to discuss in this paper the propriety of the problem of comparing sensitivities.

maximum of intensity, or retinal inertia; the relative rate of fatigue to the different colors; after-image and contrast sensitivity, etc.[7] In fact there is not a quantitative problem dealing

[7] It is conceivable that two points of view may be held with regard to what is meant by after-image and contrast sensitivity. (1) After-image and contrast sensitivity may express a relation between the amount of light required to arouse after-image and contrast sensations and the unit of light used. (2) It may express a relation between the amount of light required to arouse the after-image and contrast sensations and the amount required to arouse positive sensation. If the former view should be held it will be convenient to start with stimuli equalized in energy, and to determine the relative amounts of light required to arouse the after-image or contrast sensation by means of a sectored disc. If the second view should be held, the energy of the lights used may first be rendered proportional to the sensitivity of the eye to the colors in question; and the liminal values may then be determined by means of the sectored disc. In each case the relative sensitivity may be expressed by the inverse ratio of the open to the closed sectors.

Similarly two views may be held with regard to the determination of the comparative rates of fatigue, and of the development-time of sensation. (1) Lights equalized in energy may be used. (2) The energy of the lights may be made inversely proportional to the sensitivity of the eye to the different colors.

The need in both the above cases is equally great for a method of regulating and determining the amounts of light to be used in terms of a common unit of measurement. For example, in the second case two ways might be conceived of making the amounts of the colored lights proportional to the eye's sensitivity to these lights. (1) The limens might be determined and the intensity of the lights always be kept directly proportional to these liminal values. But the ratio needed to maintain this proportion could not be established unless some means were available of measuring the limen-values in terms of a common unit. And if this were established, we have no right to assume that it expresses the relative sensitivity of the eye to the colors in question when greater amounts of light are used. To make this assumption, we would have to maintain (a) not only that Weber's law holds for colored as well as for white light, but also that the ratio of increase which gives the just noticeable change in intensity is the same for all colors. We do not even know that there is a constant ratio over any considerable range of the intensity scale for even a single color. (b) We would have to maintain that this ratio is the same at the limen as at greater intensities, in other words, that Weber's law holds down to the limen. The consensus of opinion among investigators is that this is not true. (2) A curve may be constructed for the particular observer in which just noticeable changes in sensation are plotted along one coordinate and the energy changes required to give these changes in sensation are plotted along the other coordinate. The subjective equation, then, would be made by choosing points on the curves for each of the colors all representing the same number of just noticeable changes in intensity of sensation from the limen. The amounts of light required to give these equally intensive sensations could then readily be read off from the energy coordinate of the curve. The energy measurements required to construct such a curve would be comparatively simple, for once the limen-value was measured in terms of energy units, the remainder of the values could be determined by means of the sectored disc, that is, the energy change required to produce a just noticeable change in sensation is directly proportional to the ratio of change of open to closed sectors in the disc.

with the comparative functioning of the retina to the different colors in which there does not seem to be a need for the regulation and estimation of the stimulus in terms of a common unit of measurement. It is the purpose of the writers to extend the work as fast as possible into these related fields.

"(3) We wish to make a careful study of the sensitivity of the peripheral retina, quantitative[8] and qualitative, in a large number of meridians. In general too much uniformity has been assumed with regard to the sensitivity of the peripheral retina.

[8] The following are two of the points we wish to take up: (1) A determination will be made of the ratio of sensitivity of peripheral to central retina from point to point for a single color in several meridians. This will show at what rate the retina falls off in sensitivity in a single meridian, and how uniform this decrease is in the different meridians. We have found in a preliminary study that this knowledge is greatly needed in explaining certain phenomena of the peripheral retina. Futhermore, when this determination is made for each of the colors with which we wish to work, the ratios of sensitivity for these colors at all the points can be calculated and a definite answer can be given to the question whether or not uniformity of ratio obtains throughout the retina. This question has been given considerable importance in the discussion of color theories. (2) The limits of sensitivity will be investigated. In general two problems are involved here. (a) The limits may be considered in relation to the comparative sensitivity of the retina to the different colors. (b) They may be considered in relation to existing color theories. In the first of these problems the limits should be obtained with stimuli equalized in energy. So obtained the results will constitute merely another expression of the comparative sensitivity of the retina to the different colors. The second problem is more complicated and will later be made the subject of a separate paper. A word indicating its relation to our present plan of work may, however, not be out of place here. It may be logically assumed, for example, that the Hering theory demands that wherever the blue-sensing substance is found, the yellow-sensing substance must also be found. We have no means of knowing where these substances are except by the sensation aroused. Speaking in terms of the theory, then, we have a right to assume that wherever the blue sensation can be aroused the yellow sensation should be able to be aroused also, provided a sufficiently intensive stimulus be used. If, therefore, in passing towards the periphery of the retina, a point be found where blue can be aroused and yellow can not, the evidence will be strongly in favor of the conclusion that no yellow substance is present, unless it can be shown that elsewhere in the retina so much greater energy of yellow light than of blue is required to arouse sensation that the amount needed for this far peripheral point is greater than can be obtained. To establish this point the comparative sensitivity to these colors would have to be obtained at various points in the retina. This would involve the determination of a ratio based upon the amounts of blue and yellow light required to arouse sensation. Two methods of measurement may be used. (a) The amounts needed may be measured directly by means of a thermopile of the type we use, or other sensitive radiometer. In a determination of limens the number of readings required would render this method tedious. (b) The energy of the two lights may be made equal by means of a thermopile and the final amounts required to arouse sensation may be secured by means of a sectored disc. From the ratio of open to closed sectors the amount the light is cut down in each case may be calculated and the ratios of energy may be determined from these amounts.

Generalizations of great importance to color theory have frequently been based upon the results of work in which careful investigation was made in only one or two meridians. The conception of stable colors, and its application in support of the Hering *Urfarben* may be taken as a fair example of a sweeping conclusion which is based upon work too limited in its range. With a careful standardization of factors, an investigation in any considerable number of meridians shows that stable colors do not exist.[9] Many other points of interest have come out in our more detailed study of the peripheral retina. For example, we find in the periphery of the normal retina small areas which are exact replicas of the Schumann case of color-blindness.

"(4) We wish to conduct our investigation in full daylight instead of in the dark-room. This is to eliminate the influence of the field surrounding the colored stimulus and of the preexposure. When the surrounding field is black, white is induced by contrast across the stimulus color. Since the colors all differ in brightness, the induction takes place in different amounts for the different colors. This white, in proportion to its amount, reduces the action of the colors on the retina. Further, a given amount of white affects to different degrees the action of the different colors on the retina. To eliminate this twofold unequal action, the surrounding field should be made in each case of the brightness of the color to be used. This can be done by working in a light-room of constant intensity of illumination and making the surrounding field of a gray paper of the brightness of the stimulus color. In order to accomplish this, and at the same time be able to work upon any meridian of the retina we choose, we have constructed a special piece of apparatus which we call a rotary campimeter. The influence of preëxposure is even more important than of surrounding field. If the preëxposure is too black, white is added as after-image to the stimulus color. The effect of a black preëxposure upon the stimulus color is greater than the effect of a surrounding field of black, because more

[9] The following points are offered in support of the above statement. (1) A red and green cannot be obtained which in every meridian of the peripheral retina will pass into gray without an intermediate change into yellow or blue. (2) The amount of blue that has to be added to a mixture of red and green to produce gray varies from point to point in a given meridian even where the extramacular region alone is considered. Further, a series of determinations made for a given meridian will not hold for the remaining meridians. (3) A red, green, and yellow can not be obtained which will not change in color-tone in passing from the center to the periphery of the retina in a single meridian.

Blue alone of the four principal colors is stable in tone for all parts of the retina.

white is added as after-image of preëxposure than is induced by contrast from the surrounding field. This effect also can be eliminated only by working in a light-room of constant intensity of illumination and by choosing as preëxposure a gray of the brightness of the color to be used."

B. Description of Optics-Room and Apparatus.

The work was carried on in a well-lighted optics-room, 12½ x 10 ft. The room is situated on the upper floor of an isolated building and is lighted by a skylight, 8 x 7½ ft. Beneath the skylight, two diffusion-sashes, 4 x 7½ ft. are swung on hinges so that they can be raised or lowered as desired. The framework of these sashes is made of a light-weight iron. For convenience of local control of illumination, if needed, each sash is divided into four units by means of cross-pieces. The sashes are filled with double-strength glass ground on one side, so adjusted to the frame that they can be removed easily for cleaning or for the substitution of some other kind of glass in case that is desired. This glass diffuses the light so effectively that local shadows cast by the cross-pieces in the framework of the skylight are completely eliminated, while the sudden changes of illumination produced by the passage of the sun behind a cloud are reduced to a minimum. This diffusion seems to have the further advantage of reducing the yellowness of direct sunlight below the limen of sensation. At least, when working under the sash, the observer never judged a gray exposed through the campimeter-opening as yellow under any local conditions, as frequently happened when working under direct sunlight.

The room is planned also so that small changes of illumination can be produced, ranging from the intensive illumination of a south-exposure skylight to the blackness of a moderately good dark-room. Two provisions are made for this. (*a*) The diffusion-sashes are made so that any or all of the panes of ground glass can be quickly and easily taken from the sash, and anything can be substituted that is desired; or the illumination can be varied by placing layers of tissue-paper above the glass. (*b*) The room is provided with two curtains mounted on heavy spring rollers. One is a white curtain made of thin muslin; the

other is a black light-proof curtain so mounted that, when drawn, its edges are deeply enclosed in light-proof boxing extending along the four walls of the room. One or both of these curtains can be drawn any distance that is desired, and the illumination can thus be changed gradually from a very intense brightness to a fairly good blackness. To aid in getting dark-room effects, the doors of the room are carefully boxed and curtained. One requirement of a perfect dark-room, however, is lacking, namely, the walls and floor of the room are painted white. This is because it is of advantage in the light-room work, and because complete blackness is not needed in the type of work for which the room is devised.

The apparatus used in the investigation consists of a rotary campimeter devised to meet the requirements of the task in hand by Dr. C. E. Ferree[10] of Bryn Mawr College. The object of this apparatus is to add to the vertical campimeter the rotary features of the perimeter and thus to allow investigation of every possible meridian of the retina with as much ease and precision as was possible with the old form of campimeter in the nasal meridian only, or at most, in the nasal and temporal meridians. The apparatus consists of two parts with proper supports and accessories; a stimulus screen, and a campimeter screen which rotates on a collar around a circular support. The stimulus is exposed through an opening in the center of the campimeter screen. One arm of the framework of this screen carries the fixation-points, and also a right-angled extension which allows fixation to be given at an excentricity of 92°. This arm may be rotated to any position desired, and thus any meridian of the retina may be explored. In order that the sensation received in the peripheral retina may be accurately expressed in terms of color- and brightness-values of the central retina, the fixation-arm of the screen is further provided with a small detachable motor upon which may be rotated the proper combination of discs for matching peripheral sensation. This increases greatly the definiteness of work on the sensitivity of the peripheral retina.

[10] For the orginal description of this apparatus, see C. E. Ferree. Description of a Rotary Campimeter. Amer. Journ. of Psychol., 1912, XXIII, pp. 449-453.

The feature was added to the apparatus so that complete maps might be made of the changes in the sensitivity of the retina from center to periphery and from one meridian to another, with tables showing the value of the changes from point to point.

Photographs of the skeleton apparatus and of the front and back views of the campimeter in readiness for use are appended.

Figure 1 shows the skeleton apparatus. It consists of the following parts: supporting base, frame for campimeter screen, and frame for the stimulus card. The supporting base consists of a horizontal steel bar, 83 cm. long, supported by two iron tripod rests (B and B′). To this bar are clamped two uprights (C and C′), which are adjustable along its length. The anterior upright (C) supports the frame on which the background of cardboard and the campimeter screen (D) are fastened. The posterior upright (C′) supports the stimulus frame (E). The height from the table of each of these frameworks is adjustable by means of set-screws (F and F′). The framework for the campimeter screen consists of central support and radiating arms. The central support consists of a stationary brass ring,[11] about which rotates a larger brass collar (H), 20 cm. in diameter. The back surface of collar (H) is graduated from 0° to 360°. To this collar are fastened the radiating arms. There are eight of these arms, one for each 45° mark of the graduated collar. They are made of steel and are 2 cm. broad and 40 cm. long. The eighth arm (I-I′) differs from the other seven. It forms a right angle, one side of which is in the plane of the background and the other in front of this plane. The part in the plane of the background is 30 cm. long, and the part at right angles to this

[11] This ring was made large in diameter for two reasons. (*a*) The ring had to be made very thick in order to give sufficient rigidity to support the campimeter screen and to furnish proper attachment for the rotary collar. Had the circumferance been small, the effect of the ring would have been that of a short tube. If the stimulus were viewed through a short tube, an induction factor would have been involved which would have been difficult, if not impossible, to standardize. The opening in the ring was, therefore, made considerably larger than any stimulus we wished to use in order to avoid the introduction of this factor. (*b*) The large circumference of the ring makes the apparatus available for investigating the effect upon sensitivity of varying the size of stimulus.

plane is 28 cm. long. The arm is graduated from 18° to 57° along the section that lies in the plane of the background and from 57° to 92° along the section at right angles. The graduations are based on the arc of a circle of 25 cm. radius. The arm is also split lengthwise to form two narrow arms, each 1 cm. wide, so separated that there is an opening (J) 0.8 cm. in width between them to admit the shank of the motor for rotating the discs needed to match the peripheral sensation. The opening to admit the shank of the motor may be clearly seen in all the pictures of the campimeter. The motor is shown at K on the right of Figure 1 and more clearly on the left of Figure 3. It has a shank 4 cm. long and 0.3 cm. in diameter, which can readily be thrust through the opening (J). The weight of the motor is so great that it can not be clamped to the arm (I-I′) and thus be shifted with the arm as the retina is tested in different meridians. It has then to be supported so that it can readily and quickly be moved to any point in any meridian to which the arm (I-I′) may be rotated. This is accomplished by the use of two rods—one vertical (L) and the other horizontal (M). The vertical rod (L) may be clamped to the table or other support on either side of the campimeter, and M is clamped to L. The vertical adjustment for any setting of the motor can thus be made along L and the horizontal adjustment along M. Holes are punched in each of the eight arms at six or more places to allow the insertion of small metal fasteners to hold the background screen to the frame. The stimulus frame may be seen at E. It is 20 cm. square and carries a groove for the insertion of the stimulus card. The stimulus card may be made of whatever colored paper the experimenter desires to use.

Figure 2 shows the front view of the campimeter in readiness for use; and Figure 3, the back view. A cardboard background has been fastened to the steel arms by means of paper-fasteners. Since the background is fastened to the arms attached to the brass collar (H), a circular gap is left at its center. This gap is filled by a disc (N), shown in Figure 3, which has been fastened to the arms just outside of the collar (H). The disc is 27 cm. in diameter and contains the stimulus-opening (O), the size

of which may be varied to accord with the purpose of the investigation. In the experiments reported in this paper, it was 15 mm. in diameter throughout. In order to complete the graduations on the fixation-arm to the stimulus-opening, disc (N) is graduated from 0° to 18°. A background 40 cm. in height is fastened to the extension arm (I). In the picture a paper screen made of No. 7 of the Hering series of grays has been attached by thumb tacks to the cardboard background. A strip of paper of the same quality as the background is placed along the opening (J), and the graduations from 0° to 92° are pricked on this strip as indicated by the markings on the back of disc (N) and arm (I-I′). These constitute the fixation-points. The card in the stimulus frame (E) is seen through opening (O). A disc (P) composed of black and white sectors has been placed on the motor (K).

The method of using the apparatus is as follows: The observer is seated in front of the campimeter screen with his head held in a rigid position by means of a mouthboard bearing the impression of the teeth in sealing wax. Since the graduations of the fixation-arm are based on the arc of a circle of 25 cm. radius, the distance of the eye from the stimulus-opening is chosen as 25 cm. The position of the eye in the observing plane may be obtained according to the method described by Fernald.[12] In order to facilitate excentric fixation in the nasal and temporal meridians, the head should be turned 45° nasalwards or temporalwards, as the case may be. With the head so placed, the eye can swing easily from the stimulus-opening to a fixation-point whose excentricity exceeds 90°. The unused eye is closed and covered by a bandage. The arm (I-I′) is placed in the meridian desired, the position being indicated by the graduations on the collar (H). The experimenter covers the stimulus in the stimulus frame with a card, which we shall call the preëxposure card, while the observer takes the fixation required. At a signal given by the observer, the preëxposure card is withdrawn, the stimulus is exposed for three seconds, and the preëxposure card is replaced

[12] Fernald, G. M. The Effect of Achromatic Conditions on the Color Phenomena of Peripheral Vision. Psychol. Rev., Monograph Supplements, 1909, X., p. 18.

over the stimulus. The observer is required to rest the eye after each observation. Further provisions against fatigue are made by periods of rest after each fifteen minutes of observation.

When it is desired to measure the stimulus as seen in the peripheral retina in terms of brightness- and color-values of the central retina, the motor shown at K in Figures 1 and 3 is used. The method of making the measurement is as follows: If a direct vision judgment, for example, of the appearance of yellow at 25° in the temporal meridian is wanted, the cord (R) carrying a movable fixation-point, seen in Figure 2, is fastened in front of the 25° point on the graduated background. The observer, in position, fixates the 25° point and brings the movable point in line with the eye and the 25° point. This point then serves as the new fixation-point, and the graduated strip covering the opening (J) is removed. The required discs are placed on the motor immediately behind the new fixation-point, and their proportions are changed until the observer judges that the sensation aroused in the periphery is matched by that aroused in the center by the measuring-disc on the motor. In making this judgment, the method of ascending and descending series was used.

In this investigation, stimuli of blue, yellow, red, and green pigment papers of the Hering series were employed. White, black, and gray papers of the Hering series served to make the backgrounds. Results were obtained from three observers: Miss Campbell, *C*, graduate student in Bryn Mawr College, who had no knowledge of the problem in hand, Dr. Ferre, *B*, and the writer, *A*.

C. Determination of the Brightness of the Colored Stimuli Employed in the Investigation.

At every turn in our problem, it was necessary to know the black-white-values of the colored papers that formed our stimuli, as they appeared in the central and peripheral retina at full and decreased illumination. It was thought best, therefore, to devote a separate chapter of our report to a discussion of the methods used in determining these values. The method of flicker photometry was used throughout except at the limit of peripheral color vision, where it was possible to use the method of direct com-

parison. The black-white-values of the colors were determined for the central retina by means of the Schenck *Flimmer Photometer.* As this apparatus is not adapted to indirect vision work, it was necessary to devise a means by which the brightness of the stimuli at any point in the peripheral retina could be determined by the flicker method. The conditions of our experiment made it essential that these determinations be made not only in terms of black-white-value but also of colorless pigment paper, the brightness of which would approximately be the same as that of the colored stimulus. In order to make the latter determination possible, a series of gray papers varying in brightness by very small amounts was required. The Hering papers, ranging in number from 1 to 50, were found to furnish a series which varied in brightness by amounts sufficiently small to serve our purpose.

The use of the flicker method in photometry is based on the fact that two surfaces are considered equal in brightness when upon their alternation one with the other at a certain favorable rate of speed, no experience of flicker results. Obviously a very important point in the method is to determine what this rate of alternation should be. It should be determined empirically for each observer in a preliminary experiment. To make the determination we must be able to produce known brightness differences in different parts of the scale and to try the effect on flicker of different rates of speed for these brightness differences. This can be accomplished by making the preliminary experiment with colorless surfaces, for very small differences in brightness between two colorless surfaces can be estimated by the method of direct comparison. (This could not be done if one or both of the surfaces were colored.) Working then with colorless surfaces by the aid of the method of direct comparison, not only do we know at every stage of the experiment how much brightness difference is produced, but we standardize the flicker determination in terms of the method of direct comparison to which all indirect methods of determining brightness equality must conform if their results are to be of any value. In making our preliminary determination, then, colorless surfaces should be used and that rate of alternation, equal to or in excess of the

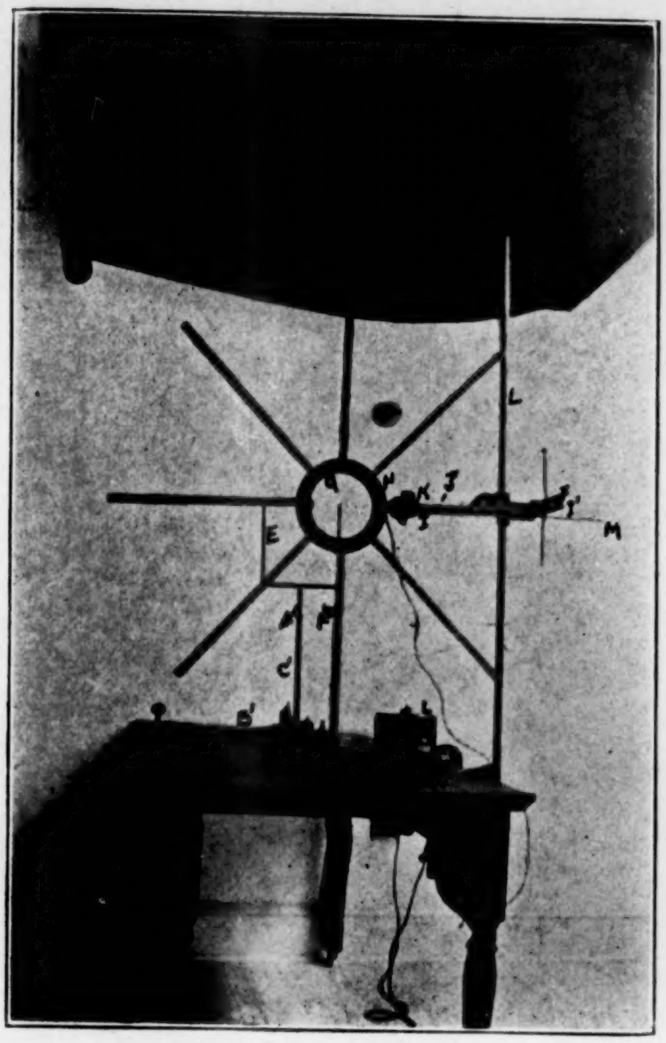

FIGURE I

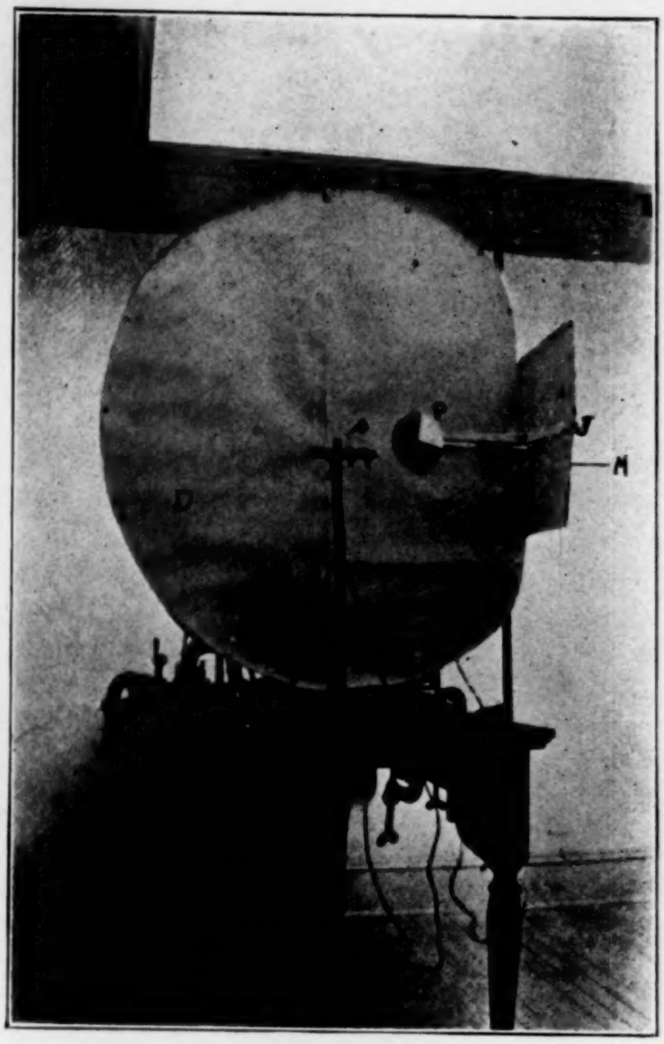

FIGURE II

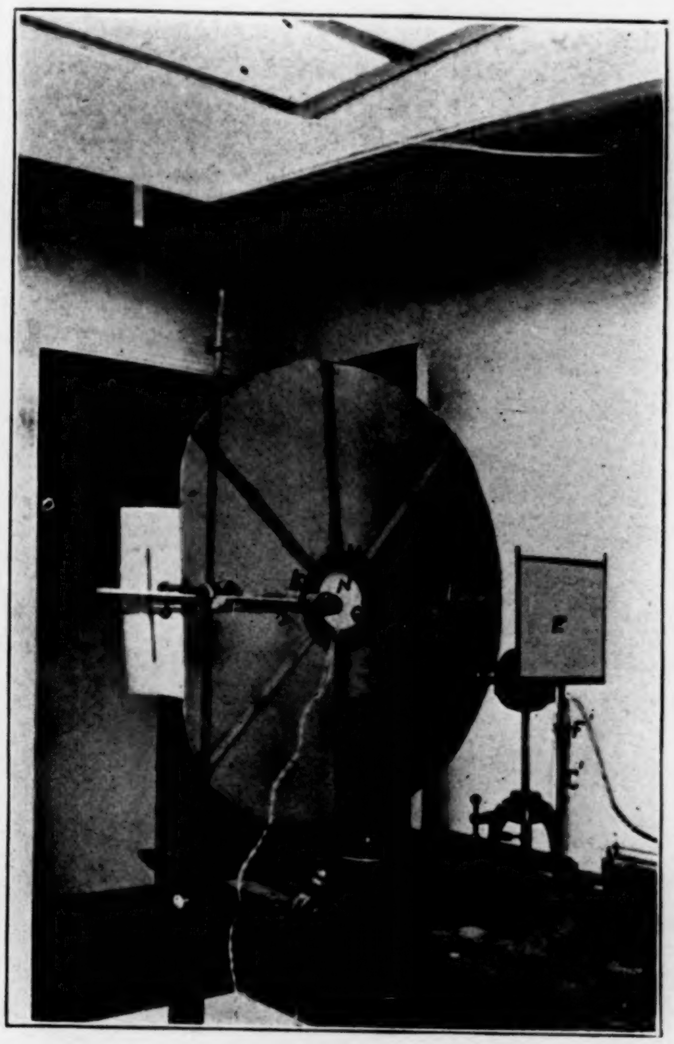

FIGURE III

fusion rate for the color in question, should be selected at which the smallest difference in brightness between the two surfaces produces flicker. This speed may be considered as giving the maximum sensitivity to the method for the given observer and may be used for that observer in the color work. Applying this method to the determination of the brightness of a colored paper, we may consider that a colored and a gray paper are of equal brightness when no flicker is produced by the rotation of equal sectors of each at the chosen rate of speed. In order to prevent induction from the surrounding field, the rotating disc should be viewed through an opening in a screen of the same brightness-value as the disc itself. This requires that the gray sector, the colored sector, and the screen all be of equal brightness-value. The final value of this brightness must, however, be reached by a series of approximations. That is, the gray sector and the screen must at each trial be chosen of the same brightness, and both must be changed alike until a gray is finally obtained which does not produce flicker when it is rotated with the colored sector at the chosen rate of speed. Owing to the great number of steps in the series of approximations needed to reach the gray-value of the color, it was impracticable to change the large campimeter screen at each step. Moreover, to prevent brightness induction over the stimulus, it was not necessary to have so large a part of the surrounding field, as was comprised in the entire screen, of the same brightness as the stimulus. Squares 30 cm. on a side were found to be quite adequate for the purpose and to have the practical advantage that they could be quickly and easily changed. Since the sensitivity of the retina to flicker varies from point to point as we pass from the fovea outwards, it is found to be important that the opening in the screen be made small so that the area of the retina stimulated shall be uniformly sensitive to flicker. And, further, since the area of the retina influenced by a given stimulus decreases as we pass from the fovea to the periphery, because of decrease in the visual angle, it is necessary that the stimulus-opening be proportionately increased in the peripheral observations, in order to maintain the size of the stimulated area of the retina constant. Both of these conditions were met sufficiently accurately for our purpose, by using two

openings of different size, the smaller to be employed at all points from the fovea to 20° peripheralwards, and the larger to be used from the 20° point to the extreme periphery.

The method used to determine the brightness in terms of gray paper of a given color in central vision was as follows. From the series of squares of gray papers having the smaller of the two sizes of stimulus-openings (3 mm. x 1 mm.) one was selected which was judged by the method of direct comparison roughly to approximate the brightness of the color in question. This square was fastened upon the campimeter screen so that the stimulus-opening passed vertically through the center of the opening in the original screen. A disc compounded of 180° of the given color and 180° of the gray of the brightness of the square, was rotated behind the stimulus-opening and the observation made for flicker. Lighter and darker grays were in turn substituted in disc and screen and the observation was repeated. The gray which produced no flicker at the chosen rate of speed is, in terms of the method, the gray of the brightness of the color. The determinations were not at all difficult nor uncertain. Flicker was readily discernible in the gray lighter and darker than the one which was chosen, at the speed of rotation at which the one chosen showed no flicker. Our determinations showed that at the standard illumination[13] used throughout the work, the method of obtaining which will be discussed later, the brightness of Hering blue for central vision equalled that of Hering gray No. 41; of red equalled gray No. 24; of green equalled gray No. 8; and of yellow equalled gray No. 2. These values were the same for all of our observers.

For the determination of the brightness of the colored stimuli in peripheral vision, the same method was used with the exception that at points in the periphery beyond 20°, the screens having the large stimulus-openings, 15 mm. in diameter, were used. The results of the peripheral experiments differed from the central at standard illumination only in case of blue. Blue was found to lighten in the periphery so much that gray No. 21 was determined

[13] Measured in foot-candles by means of the Sharpe-Millar portable photometer, the standard illumination equalled 390 foot-candles.

by one observer to equal it in brightness. The determinations at the peripheral limit of sensitivity to color were made by the method of direct comparison. On the campimeter was mounted a gray screen for each of the colors in turn the brightness of which was such that when the stimulus was observed beyond the limits of color sensitivity, the color in each case changed into the gray of the brightness of the screen. If a gray lighter or darker was used, the stimulus appeared either darker or lighter than the screen.

The black-white-values of the colors for peripheral vision can not be determined directly because for the direct determination the Schenck *Flimmer Photometer* with its graduated sectors of black and white or some similar device must be used. This photometer is not adapted for peripheral vision work. A determination, then, had to be made with the photometer in the central retina for the grays which had been found by the method described in the preceding paragraph to equal the colors in brightness in the peripheral retina.

In one section of the investigation, it was found necessary to work at decreased illumination, and to know the brightness of the colored stimuli under these conditions. The decreased illumination was obtained by drawing the black curtains, until the illumination was slightly less than that of a cloudy afternoon.[14] The colors appeared a little less saturated, and slightly altered in color tone. The green was a trifle bluish, the yellow was changed toward orange, and the blue appeared slightly reddish. Determinations were made at this illumination according to the method described above, of the brightness of the colors in central and in peripheral retina. The results are stated in Tables I and II. The first column shows the white-black-values of the stimuli at standard illumination in central vision; the second shows the same values in terms of the Hering gray papers; the third represents the brightness-values in peripheral vision at the limit of sensitivity; and the fourth and fifth columns show the brightness of each stimulus at the center and at the periphery under conditions of decreased illumination.

[14] Measured in foot-candles by means of the Sharpe-Millar portable photometer, this decreased illumination equalled 1.65 foot-candles.

Table I records the results of Observer *A;* Table II those of Observer *C.*

TABLE I.

A. Showing the brightness-values of the Hering principal colors at standard and decreased illumination.

Stimulus	Brightness at Standard Illumination: At center		Brightness at Standard Illumination: At limit of sensitivity in periphery	Brightness at Decreased Illumination: At center	Brightness at Decreased Illumination: At limit of sensitivity in periphery
Yellow	white 236° black 124°	gray no. 2	gray no. 2	gray no. 2	gray no. 3
Green	white 100° black 260°	gray no. 8	gray no. 8	gray no. 8	gray no. 5
Red	white 41° black 319°	gray no. 24	gray no. 24	gray no. 24	gray no. 50
Blue	white 15° black 345°	gray no. 41	gray no. 28	gray no. 35	gray no. 13

TABLE II.

Observer C.

Yellow	white 236° black 124°	gray no. 2.	gray no. 2	gray no. 2	gray no. 3
Green	white 100° black 260°	gray no. 8	gray no. 7	gray no. 7	gray no. 4
Red	white 41° black 319°	gray no. 24	gray no. 24	gray no. 24	gray no. 50
Blue	white 15° black 345°	gray no. 41	gray no. 21	gray no. 35	gray no. 7

Whether or not the peripheral retina functions differently from the central retina and must, therefore, be assumed to possess a different sensory mechanism, is a question of considerable importance to theories of color vision. Upon this question the results shown in Tables I and II have a direct systematic bearing. But since the comparative functioning of central and peripheral retina will be made the subject of a later report of work already completed by the writer, the significance of these results need not detain us here. We need only note in passing,

that the brightness changes that occur when a stimulus is carried from central to peripheral vision are similar to those that obtain in central vision when the illumination is decreased. With regard to this point our tables show (*a*) that in the peripheral retina at standard illumination, the colors have very nearly the same brightness relations that they have in the center at the decreased illumination we used; and (*b*) that the brightness relations of the colors seen in the peripheral retina at decreased illumination approximate those of the colors in the center when the illumination is further decreased. These latter changes known as the Purkinje phenomenon are in the following directions: blue and green relatively lighten; red and yellow relatively darken.

In Tables I and II, showing the comparative brightnesses of the color sensations at center and periphery, the lightening of blue and green and the darkening of red in the periphery are sufficiently pronounced to need no comment. But measured by these results, the change in yellow seems to be insignificant. If, however, yellow is observed in the periphery at decreased illumination and is compared with gray No. 2, that is, the brightness of yellow both in center and periphery at standard illumination and in center at decreased, it appears to be much darker than the gray screen. Contrast from the screen exaggerates this darkening to some extent but the change in the brightness of the sensation due to peripheral stimulation alone is considerable.

D. The Factors Investigated.

The factors we have investigated with regard to their influence upon the color observation are: (1) the brightness of the stimulus; (2) the brightness of the field surrounding the stimulus; (3) the brightness of the preëxposure; and (4) the general illumination of the retina.

1. *Brightness of the Stimulus.*

It will be remembered from the historical discussion (p. 45 ff.) that the four men,—Bull, Hegg, Hess, and Baird,—who recognized the need of equating the intensity of colored stimuli for a determination of the relative limits of color sensitivity, equated them also in brightness. They apparently assumed the need of

this equation without having investigated the influence of the brightness difference between the colors upon the breadth of the color zones. As a result of a careful investigation of this question, we are able to show that not only is no advantage gained by equating the brightness of colors when determining their limits of sensitivity, but a positive disadvantage is suffered. The following reasons may be cited in support of the latter statement. (*a*) The quality of certain colors is changed when their brightness is altered. This disadvantage, first mentioned by Chodin, was a source of great difficulty to Hegg, as we have seen (p. 74).[15] (*b*) Colored stimuli which have been equated in brightness are necessarily reduced in intensity. For this reason, no true nor comprehensive estimate of the color sensitivity of the retina can be obtained with stimuli equated in brightness. (*c*) The technique involved is extremely cumbersome.

Our investigation of the influence which the brightness difference between the four principal colors exerts upon their limits covers four points. (*a*) The work on the first took its start from Hegg.[16] Hegg apparently assumed that the difference in the brightness of the four colors,—red, green, blue, and yellow,—at full saturation is sufficient to affect their limits, and, therefore, that they must be equated in brightness before a determination of their relative limits is made possible. With the view of testing the validity of this assumption, we sought to ascertain whether a brightness change in any one of the four colors, equal to the maximal brightness alteration made in Hegg's equation, affects the limits of sensitivity to that color, provided the alteration is produced without changing the amount of colored light coming to the eye. The test was made doubly strict by varying the colors both toward white and toward black, thus covering a variation whose range was twice as great as was required. That is, both white and black in turn were added to each of the colors in

[15] Mrs. Franklin remarks concerning Hegg's oil papers: "Of the 'normal' colors prepared by Hegg, the red and the yellow would not strike the plain man as at all deserving of the name" (Psychol. Rev., 1897, IV., p. 96).

[16] A start was taken from Hegg, in preference to the other three investigators, because he is the only one who gives adequate numerical data concerning the extent of brightness alteration he made in obtaining this equation.

amounts equal to Hegg's maximal change, and the limits of the stimuli thus obtained were compared with each other, and with the limit of a stimulus equal to them in physical intensity and to the original color in brightness. No effect whatever on the limits was found as a result of these brightness alterations. (*b*) We next sought to ascertain whether a brightness equation is necessary when working with the standard pigment papers of the Hering series. A determination of the maximal brightness difference between the colors was made at the limit of sensitivity to each, and the above experiments were repeated using the maximal value obtained in these determinations, as the amount of variation. In no case were the limits affected. (c) Following Hegg's plan of equating the four colors to one of mid-brightness, we next determined the maximal amount of change required to equate the standard Hering colors to the brightness of green. Since the amount of change was obviously much less than the variations used in (*b*), it was not necessary to repeat the experiments on the limits of sensitivity with this amount of variation. In two ways, then, we shall have shown that it is unnecessary to equate the Hering colors for brightness when determining their relative limits of sensitivity, since neither the maximal amount of change required to bring them all to a medium brightness, nor the maximal amount of brightness difference between the colors, has any effect upon the color limit when this change is applied as a variant in the direction of either white or black, provided that the amount of colored light coming to the eye remains unaltered throughout. These results may seem contradictory to the statement made by certain other writers and by ourselves[17] that dark colors appear more saturated than light colors of equal physical intensity, that is, white exerts a greater inhibitive action than black upon color. This brings us to our fourth point. (*d*) We have to explain why these brightness changes which are known in general to affect the sensitivity of

[17] Ferree, C. E. and Rand, G. Colored After-image and Contrast Sensations from Stimuli in Which No Color Is Sensed. Psychol. Rev., 1912, XIX., pp. 215; An Experimental Study of the Fusion of Colored and Colorless Light Sensation: The Locus of the Action. Journ. of Philos. Psychol. and Scientific Methods, 1911, VIII., pp. 294-297.

the retina to color do not change the limits of color. The explanation, as will be shown on p. 104, is found in the extreme rapidity with which color sensitivity of the retina falls off near the limits. The amounts of brightness dealt with in the above cases do not produce a sufficient change in the saturations of the light and the dark color to cause their limits to differ by even 1°, because the stimuli reduced in intensity by this amount of brightness are still sufficiently intensive to cause the color limits to occur within the zone of rapid decrease in sensitivity. If the stimuli had given a very small amount of colored light to the eye, and the limit of sensitivity had consequently occurred nearer the center of the retina where the sensitivity falls off more gradually, the difference in saturation between a dark and a light color of equal physical intensity, might have been sufficient to cause the latter to have a narrower extent of visibility. But since the amount of intensity at which this exception occurs is much less than is ever likely to be used in investigating the color limits, the exception can scarcely be entitled to more than theoretical consideration. The writer regrets to report that she has not carried on this investigation with spectral light. While she has no reason for believing that the results would in general be different, still for the sake of knowing the exact values of the brightness quantities obtaining in case of spectral colors, she hopes to make the investigation in the near future.

To investigate these points, it was necessary to devise a method whereby the brightness of the color can be altered without changing the amount of colored light coming to the eye. When one is working with pigment papers, the brightness of the stimuli can easily be varied without changing the intensity of the stimulus. For example, discs can be compounded of 260° of yellow and 100° of white, 260° of yellow and 100° of black, 260° of yellow and 100° of the gray of the brightness of yellow. In these cases we have, in order, a tint of yellow, a shade of yellow, and a yellow reduced in saturation but not changed in brightness, —all giving the same amount of yellow light to the eye. If it should be desired to make the tints darker and the shades lighter, the brightness sectors can be chosen of white or black in any proportion that is required.

In determining the size of the brightness sector to be used for the first point in this investigation, we are obliged to proceed largely by inference from Hegg's rather meager report of his work. He had equated the peripheral brightness-values of his four stimuli to green. In doing this, 84° of white and 5° of black were added to red. No statement whatever is made by him with regard to the amount of white and black added to blue and yellow. These amounts have, therefore, to be inferred. In doing so, care was taken to make the amount sufficiently large to give our test due rigor. We have mentioned that blue lightens in the periphery until its brightness is much like that of red. For Observer *A* it is slightly darker than red, for *C* slightly lighter. It is fair, then, to assume that 100° represents the maximal brightness difference that Hegg found to obtain between the colors in their peripheral values. Observations were taken from sets of discs composed of sectors of 260° of each of the four principal colors and 100° in turn of white, of black, and of the gray of the brightness of the color. The surrounding field and preëxposure in each case were of the gray into which the stimulus color changed at the limit of sensitivity. Several observers were used and several meridians explored, but in no case could a difference in the limits of sensitivity be detected for the color mixed with white for the color mixed with black, and for the color mixed with the gray of the brightness of the color. Space will not be taken here to record the results for all observers in all meridians investigated. The results obtained for Observer *A* for the temporal and nasal meridians are selected as typical. They are shown in Table III.

We have seen that the alteration made by Hegg in his brightness equations, when applied to stimuli of Hering standard papers, does not affect their limits of sensitivity. We now pass to our second point, namely, whether the full brightness difference in these colored papers should be considered as in any way affecting their limits. This is somewhat different from the preceding point in which we were concerned merely to find out whether Hegg's attempt to reduce all the colors to a mid-brightness could be considered as having any effect upon their limits.

TABLE III.

A. *Showing the limits of sensitivity*[18] *when the colors are mixed in turn with* 100° *of gray of the brightness of color,* 100° *of white, and* 100° *of black without altering the amount of colored light coming to the eye.*

Stimulus	Meridian	Limit of stimulus when mixed with 100° gray	Limit of stimulus when mixed with 100° white	Limit of stimulus when mixed with 100° black
Yellow	Temporal	42°	42°	42°
Green		35°	35°	35°
Red		41°	41°	41°
Blue		51°	51°	51°
Yellow	Nasal	88°	88°	88°
Green		59°	59°	59°
Red		85°	85°	85°
Blue		91°	91°	91°

We wish here to find out whether the actual difference in brightness between the extreme members of the series, blue and yellow, affects the limits of any one of the series. To do this, our method was to determine the difference between blue and yellow at their limits of sensitivity, to vary each color toward both white and black by the amount of this difference, and to find out whether the limits of the light and the dark stimulus differ from each other or from that of a stimulus of equal intensity which has retained the original brightness of the color. This amount of variation was greater than was needed in case of red and green, because they do not differ from any member of the series by so great an amount. We have used this maximal amount, however, because we have not wished to leave room for any question as to the rigor of our test.

In order to ascertain the difference between the white-values of the colors seen in the extreme periphery, the Hering gray that represented the peripheral brightness of each stimulus as determined by the method of direct comparison at the limit of sensitivity (see Tables I and II), was mounted on the Schenck

[18] The point at which color loses all trace of its original quality is recorded as the limit of sensitivity.

Flimmer Photometer, and its white-value determined. For Observer *A,* blue was the darkest color. Its brightness was equal to white 37°, black 323°; that of red was equal to white 41°, black 319°; that of green was equal to white 100°, black 260°; that of yellow, the lightest color, was equal to white 236°, black 124°. The maximal brightness difference, then, was between blue and yellow, and was equal to 199°. To ascertain whether this brightness difference is sufficiently great to influence the breadth of the color zones, the limits of stimuli composed of 161° of each color and 199° of black, and of 161° of color and 199° of white were compared with each other and with the limit of a stimulus composed of 161° of color and 199° of gray of the brightness of the color. The first two stimuli, it will be observed, were composed of the color altered in brightness toward black and toward white by an amount equal to the difference in white-value between blue and yellow; the third stimulus retained the original brightness of the color while it sent the same amount of colored light to the eye as the other two. In every case, on either the nasal or the temporal meridian, the limit of color visibility was the same whether the stimulus was the color in its original brightness or whether its brightness was changed in either direction, toward black or toward white, by an amount equal to the maximal difference between the white-values of the colors as seen in peripheral vision.

As we have said, our test is unnecessarily severe. Not only have we lightened blue and darkened yellow by an amount equal to the difference in their white-values, but we have also darkened blue and lightened yellow by the same amount. If a brightness equation were found to be necessary, the variation would by no means be as wide as the one we have made. It would be necessary merely to darken some colors and to lighten others to a medium brightness.[19] We feel confident then in stating the following

[19] The change we have made in one direction is no greater than had to be made by Baird who equated all of his colors to the brightness of blue. Baird, it will be remembered, was forced to employ this brightness as standard because his equation of brightness was made by interposing an episcotister between the stimulus and the eye of the observer. This method permitted change only in one direction, towards black. The defects of his method

two points:—(*a*) The amount of change required to equate in brightness the colors, red, green, blue, and yellow, has no effect upon their color limits and the precaution of equating is, therefore, superfluous. (*b*) The actual brightness difference in the colors at standard saturation has no effect upon their relative limits.

While we have shown that variations of brightness in the above amounts do not affect the limits when there is no alteration in intensity of the colored light, we do not claim that there might not be a change sufficiently large to influence the limits. This would be a broader thesis than we wish to maintain. We have merely been concerned with showing that brightness alterations as great as the difference between the white-values of the Hering standard papers do not affect the limits. Strictly speaking, this is as far as our criticism of previous attempts to standardize brightness need carry us. But it is a matter of fact that a color mixed with black gives us a sensation that is more intensive than that produced by a color of equal physical intensity which is mixed with white, and that the limen of color is much lower when the color is mixed with black than when mixed with white. Brightness change, then, does affect the retina's sensitivity to color, and, within limits, the breadth of the zones of sensitivity. We have, therefore, extended our investigation to explain why changes of the order given above do not affect the color limits, and to determine roughly to what extent brightness change may be made without affecting them. As already indicated we must look for the explanation of our results to the rapidity with which the sensitivity of the retina falls off from point to point from center to periphery. If, for example, it be found that sensitivity falls off gradually from the fovea to near the limits (as determined with stimuli of full intensity,) and from that point on, it falls off abruptly, we might expect that light and dark colors of equal physical intensity will have different limits up to the point on the retina at which the abrupt

have already been pointed out. With a spectroscopic mixer as the ideal apparatus for investigations with the light of the spectrum, the brightness changes can be readily made in both directions, as they can with pigment paper stimuli.

change in sensitivity begins, and the same limits from that point on. It is obvious that in either case, whether or not there is a difference in limit, depends upon whether the difference in the inhibitive action of white and black upon the color is equal to the amount of change of intensity required to affect the limit. If sensitivity falls off gradually, a relatively small change in intensity is sufficient to widen the limit, and, if abruptly, a relatively large amount of change is required.

By way of explanation, it is our purpose to show (*a*) that the sensitivity of the retina falls off gradually to a point within 5° of the limit and from that point to the limit, it falls off very abruptly; (*b*) that the white and black sectors added to the colored stimuli in the foregoing tests did not weaken the stimuli sufficiently to narrow their limits more than 3°; and (*c*) that within the zone 3° from the limit, the difference between the apparent saturations of our light and dark stimuli was not sufficient to affect their limits.

An inspection of the results given in Table VIII and discussed in the next section (p. 117 ff.) will show the rate at which the sensitivity of the retina falls off from the fovea to the periphery and will establish our first point. The decrease is gradual from the center to within 5° of the limit, beyond which point it grows progressively more abrupt, becoming extremely abrupt from a point 3° from the limit to the limit. For example, when the screen and preëxposure of the gray of the brightness of color are used, the limen of yellow at the fovea is 18°; at 39° from the fovea in the temporal meridian, that is, 5° from the limit of yellow, it is 100°. Thus over a space of 39°, the limen has increased only 82°, and average of little more than 2° of increase per degree of retina traversed. At 41°, however, it has reached a value of 150°, an average of 34° of increase per degree of retina traversed; at 42°, a value of 240°, an average of 90° of increase per degree of retina traversed; at 43°, a value of 330°, an average also of 90° per degree of retina traversed. With regard to the second point, it will be remembered that the extreme amount of white or black we added to our colors was 199°. This left 161° of color in the stimulus discs. Table VIII

(page 119) which gives the values of the color limens at different points near the limit, shows that this amount of color is above the limen for each color at 3° from the limit. In our tests, then, we were working well within the 5° limit bounding the zone of abrupt decrease in sensitivity, as our explanation required us to show. With regard to the third point, it will be seen from the same table that, when working at the point 3° within the limit, in order to extend the limit 1°, an increase of the colored sector by amounts ranging from 65° in the case of blue to 115° in the case of green, is required. It scarcely need be pointed out that the apparent saturation of a stimulus composed of 161° of color and 199° of black is not greater than the apparent saturation of a stimulus composed of 161° of color and 199° of white by an amount equivalent to from 65° to 115° of color.

Having explained why brightness differences equal to those found in red, green, blue, and yellow papers of standard saturation have no effect upon the limits of color sensitivity, we turn next to a determination of the range within which brightness change may be made without affecting the limits of sensitivity. Two ways occur to us by means of which a rough estimate of this range may be obtained. (a) Stimulus colors at full saturation may be used and the brightness excitation be added as after-image or contrast or both. In this way the amount of colored light coming to the eye is not altered by the brightness added, that is, the physical intensity of the color in the stimulus is not affected. If we wish to use the contrast and after-image effects, the card which covers the stimulus before exposure can be adjusted so that an intensive after-image is superimposed upon the stimulus when the card is removed. By a proper regulation of this card and of the campimeter screen, which causes contrast induction across the stimulus, varying amounts of white and black can be added to the stimulus, care being taken to measure these amounts and to keep them equal, each to each. Since, according to our measurements in this region of the retina, the after-image and the contrast excitations from white are more intensive than those from black, the quality of the screen and

preëxposure designed to give dark contrast must be regulated until the brightness excitation aroused is found to be equal in amount to the white given by the black screen and preëxposure. A series of these changes can be made until a point is reached where the sensations are reduced in intensity sufficiently to allow the more saturated dark color to be seen farther out than the light color. The sum, then, of the amounts of white and black added in turn to the stimulus, will give the range of brightness change that may be made in a stimulus of full intensity without causing the difference in brightness to be a factor influencing color limits. (*b*) Equal sectors of white and black may be added to the stimulus color until a point is reached where the darkened color is seen farther out than the lightened. This method has the disadvantage that with each addition to the brightness sector, there is a corresponding subtraction from the color sector. On the other hand, however, it may have a possible advantage over the former method in that the brightness excitation that is added to the color is aroused by light-waves, as is the case with the standard colors whose brightness differences gave rise to our problem; hence any theoretical questioning is obviated as to the quantitative equivalence of the action of a brightness excitation objectively aroused to an excitation aroused as after-image or contrast. But since we can not work with colors at full saturation, the disadvantage is probably much in excess of the advantage. We can doubtless come much closer to the value we are seeking by the first method. As the work by this method is not completed, its report will be deferred until a later paper. The results obtained by the second method are given in Table IV. In this table we have shown how much the colored sector may be reduced by the addition of black and white, without changing the limits for the darkened and the lightened color. If a further reduction is made, the darkened color will be seen at a greater excentricity than the lightened color. The results show that 240° of black, white, or gray of the brightness of color may be added to yellow and the limits for the three shades of color so formed will still coincide; 225° to red; 215° to blue; and 230° to green. Since, roughly speaking, the amount of inhibition will be inversely proportional to the amount of color

present, it is obvious that if the colors could have been maintained at full intensity, as they usually are in the investigation of sensitivity, a still greater brightness change would have been possible. While we may not have determined by this method just how much brightness difference there may be between colors at full saturation without affecting the limits, we have shown beyond doubt that there may be much more than is found between the standard pigment colors.

Table IV gives some of the results of this investigation for Observer *A* in the temporal meridian. Each observation was taken with screen and preëxposure card of a gray of the brightness of the color. Since the results in the nasal meridians are very similar to these, space will not be taken to report them. As the sensitivity of the retina falls off gradually in all directions until within 5° of the limit, the limen at this 5° point is almost identical, whatever the meridian.

TABLE IV.

A. *Showing how much white, black or gray of the brightness of the color we may add to a colored stimulus and still have a coincidence of limits for the three shades of color, providing the amount of colored light coming to the eye is kept constant.*

Stimulus	Value of colored sector	Value of brightness sector (gray of brightness of color, white, or black)	Limit of sensitivity when color is mixed with gray of brightness of color	Limit of sensitivity when color is mixed with black	Limit of sensitivity when color is mixed with white
Yellow	260°	100°	42°	42°	42°
	180°	180°	40°	40°	40°
	90°	270°	37°	38°	37°
	120°	240°	40°	40°	40°
	105°	255°	39°	40°	39°
Green	120°	240°	30°	31°	30°
	130°	230°	31°	31°	31°
Red	120°	240°	37°	38°	35°
	135°	225°	39°	39°	39°
Blue	135°	225°	48°	48°	43° [20]
	145°	215°	49°	49°	49°

[20] The decided narrowing of the limit of the blue stimulus in this case

But there is more than one kind of problem which deals with peripheral color sensitivity. To avoid any possible misunderstanding of our position, a word may be added to show when it is of advantage and when of disadvantage to equate stimuli in brightness. (*a*) When investigating the limits of color sensitivity and when the brightness of the surrounding field is the same as the brightness of the stimulus color, a brightness equation of the different colors, within the limits we have just determined, is not only unnecessary, but a positive harm. This, moreover, is the proper regulation of the brightness of the surrounding field for all investigations of the relative and absolute limits of sensitivity and of the limens of color at different points on the retina. (*b*) When, however, the brightness of the surrounding field is different from that of the color, the factor of the induction of the screen must be taken into account. Since brightness contrast follows the law that maximal contrast occurs when there is a maximal brightness opposition, different amounts of contrast will be induced across colors of different brightnesses. But under these conditions, only one legitimate problem can arise, namely, to test the effect of the screen. There are two points to this problem. (*i*) Knowledge of the effect of different screens upon the same color may be desired. In this case, the problem of

is due to the following cause. For Observer *A* there is a small spot in the horizontal temporal region of the right eye that is totally insensitive to blue light. This miniature spot of blue-blindness extends from 43° to 47° in the horizontal temporal meridian. Now since the apparent intensity of the sensation aroused by the stimulus composed of 135° of blue and 235° of white was not sufficient to allow the color to be seen on the peripheral side of this blue-blind spot, its limit occurred on the foveal limit of the spot, at 43°. It may be added that spots of this type are not unusual. The writer has found in every eye she has tested one or more spots that are partially or totally insensitive to one color alone. Relative to these blind spots, the following interesting features may be noted. (a) Although totally blind to a given color, they have normal sensitivity to its complementary color. (b) They give a fully saturated complementary-colored after-image of this color to which they are blind. (c) They show the usual cancelling action between the color to which they are blind and its atagonistic color. In short, they seem to be exact replicas in the periphery of the normal eye of the unique type of color-blindness described by Schumann (see Schumann, F. Ein ungewöhnlicher Fall von Farbenblindheit. Bericht über die 1. und 2. Kongress für experimentelle Psychologie, 1904, pp. 10-13.

brightness equation would not arise. (*ii*) Knowledge of the effect of the same screen on different colors, or of the comparative effect of different screens on more than one color may be desired. In this case the colors may or may not be equated in brightness:—the question depending upon the requirements of the problem. If they are not equated in brightness, there will be different amounts of induction with each screen for each color. If they are, the colors will be altered in intensity and often in color tone. No general rule can be laid down as to equation or non-equation in these cases. Each has to be settled on its own merits and in accord with the requirements of the problem in hand. What we wish to emphasize more than anything else at this point is that, while at different times in color work, one may need to make legitimate use of a surrounding field which differs in brightness from the stimulus color, it should never be done in any investigation of the relative or absolute limits or limens of color sensitivity. The use of the perimeter and the dark-room is a notable instance of the violation of this precaution. The surrounding field of intensive blackness induces a different amount of white over each of the colors unless they are of the same brightness. And if they are equated in brightness, all the disadvantages which, as pointed out earlier in the paper, result from this equation, are suffered in the investigation. Moreover, to equate the stimuli in brightness is not to get rid of the induction of the surrounding field. We still have, after equating, a large amount of brightness induction which operates against a determination of absolute limits by tending to narrow the limits of sensitivity for all colors; and against a determination of relative limits by narrowing the different colors unequally, depending upon the difference in the inhibitive action of the same amount of white upon them.

2. *Brightness of the Field Surrounding the Stimulus.*

When a small color stimulus is surrounded by a large field of white or black, a sensation is given which consists of the color mixed with black or white, due to contrast induction from the surrounding field. The influence of the brightness of the surrounding field upon color sensitivity resolves itself, then, into the

question of the fusion of colored with colorless light sensation in central or peripheral vision, according to the part of the retina that is stimulated. The details of this fusion in central vision have been taken up by the writer working in collaboration with Dr. C. E. Ferree,[21] in which work it was shown that the effect of fusing a colored sensation with white, black, or gray is twofold. (*a*) There is a quantitative effect due to the inhibition of chromatic excitation by achromatic. White inhibits color most, the grays in order from light to dark next, and black the least. The records of all the observers used in this investigation show that the achromatic series inhibits red and yellow considerably less than blue and green. (*b*) There is also a qualitative effect. The tone of certain colors is changed by the action of the achromatic excitation. The change is greatest when the stimuli are blue and yellow.[22] Yellow, when mixed with black, gives a sensation of olive-green; and blue when mixed with white, black, or gray gives a sensation of reddish-blue.

As a factor influencing the limits and limens of the sensitivity of the retina to color, the inhibitive, or quantitative effect of the fusion concerns us more than the qualitative. As we have stated, a white surrounding field, for example, a white campimeter screen, induces black across the stimulus which fuses with and modifies the resulting sensation; while a black screen induces white. For an estimate of the amount of brightness contrast that is induced by white and black screens across yellow, green, red, and blue stimuli, the reader is referred to the section: *Quantitative Estimate of the Influence of the Change of Illumination upon the Induction of Brightness by the Surrounding Field* (p. 138). The question is considered in detail in that section rather than in the present one, because it will be necessary at that point to compare the amounts of brightness induced by the white and

[21] Ferree and Rand. An Experimental Study of the Fusion of Colored and Colorless Light Sensation: The Locus of the Action. Journ. of Philos. Psychol. and Scientific Methods, 1911, VIII., pp. 294-297. This is only a brief preliminary report of the work. A full report will be published later.

[22] How far the qualitative effects of the fusion of colored with colorless light sensation in central vision are paralleled in peripheral vision, will form the discussion of a later chapter of this investigation, not reported in this paper.

black screens at standard and decreased illumination. In that section is shown also in what way the amounts of brightness induced by the screens were estimated, and within what limits the values obtained can be said to represent these amounts. Tables XII and XIII (pp. 142-143), columns 1, 2 and 3, give the amount of contrast that is induced by the white and black screens at standard illumination across the grays of the brightness of the colored stimuli at 25° and 40° in the horizontal temporal meridian for Observers *A* and *C*. The results of these tables may be summarized as follows:

1. The amount of induction from the white and black screens increases with the distance from the fovea.

2. The amount of induction from the white screen is greater than that from the black screen.[23]

3. The white and black screens induce most across the stimuli that are farthest removed from them in brightness, and least across those which are nearest to them in brightness. That is, the white screen induces more black across the gray of the brightness of blue than across the gray of the brightness of yellow; the black screen induces more white across the gray of the brightness of yellow than across the gray of the brightness of blue.

The effect of this induction of the surrounding field may be shown by two methods: (*a*) by its effect on the limits of color sensitivity; and (*b*) by its effect upon the limens of color sensitivity.[23a] Up to this time, so far as the writer knows, the effect of the surrounding field has been estimated only by the first of these two methods, by its effect on the color limits. This method, however, estimates the effect of the surrounding field upon the color sensitivity of the extreme peripheral retina alone. By the

[23] See footnote p. 141.

[23a] Since sensitivity to color is measured by determining both the limen and j. n. d. of color, it might be thought that the effect of surrounding field could be measured in both of these ways. The determination of the j. n. d. would, however, show very little, because the induction of the surrounding field would affect both the standard and comparison surfaces. This will be true also of the effect of the brightness of the preëxposure, and of changes in the general illumination. In none of these cases has the writer considered it worth while to make the determination of the j. n. d.

second method, on the other hand, this effect can be measured in the central and paracentral regions, as well as in all parts of the peripheral retina. In order to make a complete study of the effect of the brightness of the surrounding field on color sensitivity, we have used both of these methods. The report of the work done by them is as follows:

a. The effect of the induction of the surrounding field upon the limit of color sensitivity.

Assuming that the law of brightness inhibition of color for the central retina holds for the peripheral retina, we should expect to find that, since colors have a lower limen in black than in gray or white, a white screen, which causes black induction across the stimulus, would be more advantageous to color vision than would a black screen, which causes white induction. Further, we should expect to find that a gray screen of the brightness of the stimulus, which causes no induction whatever, would be the most favorable.

An investigation of the color limits with screens of white, black, and gray of the brightness of the color, shows, however, the following facts:

1. Blue and green have widest limits with the gray screen, slightly narrower with the white, and narrowest with the black.

2. Red and yellow have widest limits with the black screen, slightly narrower with the gray, and narrowest with the white.

The color limits of Observers *A* and *C,* taken on the temporal and on the nasal meridian, are given in Table V and VI.

b. Explanation of the effect of the induction of the surrounding field on the limits of color sensitivity.

Turning to the explanation of these results, we shall here endeavor to account for the results obtained with the white and black screens. We have the following points to explain: (*a*) Blue and green have wider limits with the white screen than with the black, but the difference is comparatively small. According to the law of the action of white and black on colors, formulated from the results of work in the central retina, we should expect to find wider limits with the white screen, which induces black, than with the black screen, which induces white. Thus far, then, the results are in accord with the law, but the difference found

TABLE V.

A. *Showing the limits of color sensitivity with screens of white, black and gray of the brightness of the color.*

Stimulus	Limit with gray screen of the brightness of the color	Limit with white screen	Limit with black screen	Meridian
Yellow	44°	42°	45°	90° Temporal
Green	37°	36°	34°	
Red	43°	42°	44°	
Blue	53°	50°	49°	
Yellow	90°	88°	92°	90° Nasal
Green	64°	62°	60°	
Red	89°	87°	89°	
Blue	92°	92°	92°	

TABLE VI.

Observer C.

Yellow	49°	46°	50°	90° Temporal
Green	44°	42°	40°	
Red	45°	41°	45°	
Blue	56°	55°	53°	
Yellow	92°	92°	92°	90° Nasal
Green	87°	84°	53° [24]	
Red	92°	92°	92°	
Blue	92°	92°	92°	

between the inhibitive action of white and of black in the central retina would lead us to expect a greater effect on the limits. (*b*) Yellow and red have wider limits with the black screen than with the white. This is in direct contradiction to the law of fusion formulated for the central retina. With regard to explanation, two points must be considered. (1) The relative inhibitive action of black and white upon color must be investigated in peripheral vision; and (2) the rate of falling off in sensitivity of the peripheral retina must be ascertained.

[24] In this case, the qualitative change of green to blue caused the decided narrowing of the limit.

(1) *The relative inhibitive action of black and white upon color in peripheral vision.* The relative inhibitive action of white and black upon the colors must be investigated at all points from the fovea to the limits of sensitivity to see whether the law established for the central retina holds for all degrees of excentricity. If we find that the difference between their inhibitive actions lessens as we go towards the limits, we have a reason for the small widening of the zones of blue and green by the white screen. And if we find just within the limits of sensitivity for red and yellow that black inhibits these colors more than white does, we have a reason for the relative widening of the zones of sensitivity for these colors with the white screens, provided we can show that the effect of neither screen will carry the limits farther towards the fovea than the inner margin of this zone within which the exception is found.

To test the relative inhibitive power of black and white in the peripheral retina, the limen of color in black and white had to be determined. Two methods of procedure were possible with the apparatus used. By the first method, the stimulus was a disc with sectors of color and white or black which could be adjusted so that a liminal sensation of color was produced. In order to prevent brightness induction the screen had to be of a gray of the brightness of the stimulus used. With each addition of color to the stimulus, a change of the brightness was produced. The screen then had to be altered in brightness by an equal amount. Of the two methods of determining the brightness of the stimulus, described p. 91, the method of comparing the brightness of the colorless peripheral sensation with the surrounding field was obviously better adapted to the requirements of this observation than was the more cumbersome flicker method because the brightness of the stimulus was being continually altered. For the present case, the gray squares were used for surrounding field that had served a similar purpose for the determinations of the brightness of the stimuli in the periphery at standard and decreased illumination. The observer first made a preliminary judgment of just noticeable color, and then determined the gray that was equal in brightness to the stimulus. A square of this gray was then

mounted on the campimeter and the final determination of the limen was made. By the second method, the screens were removed and the skeleton apparatus alone was used. A disc composed of white and black sectors was placed on the motor so that it just filled the large circular ring at the center. This gave a surrounding field whose brightness could be adjusted at will. A small disc, 2 cm. in diameter, composed of sectors of the color to be investigated and black or white, was placed over the large black and white disc. The method of procedure was as follows. The observer took the required fixation, and observed the small disc to find the smallest amount of color that could be sensed when fused with white or with black, as the case happened to be. Before each determination, the experimenter adjusted the black and white sectors of the large disc, so that they equalled the brightness of the inner disc. This brightness was readily calculated from the following quantities:—the number of degrees in the colored sector, its black-white-value, and the number of degrees of white or black in the remainder of the disc.

Since the point in question was of considerable importance, both of these methods were used, the one as a check on the other. The first had the advantage of greater ease of manipulation and of employing a stimulus which was the same size as that used in the sensitivity experiments. The second had a possible advantage in the adjustment of the brightness of the surrounding field, but it was of disadvantage because the surrounding field could not be made so wide as by the former method and because a stimulus larger than that usually employed had to be used.

Results from both of these methods show the following facts: (1) As the fixation becomes more excentric, the difference in the inhibitive action of white and black decreases. (2) From center to periphery, the limens of green and blue are greater when mixed with white than when mixed with black; that is, the law of the greater inhibitive power of white holds for these colors in the periphery as well as in the center. (3) An exception to this law is found for yellow and red near the limits of sensitivity. From the center to within about 5° of the limit of sensitivity,[25] white

[25] By the limit of sensitivity is meant the widest limit of color determined at standard illumination.

has a greater inhibitive power than black over these two colors. But from this point to the limit, the reverse relation obtains, and red and yellow in this region have a greater limen in black than in white. How much this apparent exception to the law of fusion as it obtains in central vision is due to the natural darkening of red and yellow as they pass into the peripheral field of vision, we are not at this time prepared to state. Because of this darkening, there is more black fused with red and yellow than the results of Table VII express. These results represent the values of the colored and black sectors in the stimulus discs only and not the actual proportions of color and black excitations aroused.

Results are shown in detail in Table VII. They are taken from the records of Observer *A*, on the temporal meridian by the first method described. Column 1 indicates the stimulus used; column 2, the fixation at which the liminal determination was made, and columns 3 and 4, the limens of color mixed with white and black.

TABLE VII.

A. *Showing the inhibitive action of white and black upon color in peripheral vision.*

Stimulus	Fixation	Limen of color in white	Limen of color in black
Yellow	0°	40°	3°
	35°	85°	65°
	38°	95°	85°
	40°	120°	115°
	42°	290°	320°
Green	0°	45°	5°
	25°	80°	50°
	31°	130°	100°
	33°	200°	175°
Red	0°	30°	3°
	35°	80°	65°
	38°	120°	110°
	39°	135°	135°
	40°	155°	170°
	42°	290°	310°
Blue	0°	60°	10°
	35°	125°	65°
	41°	145°	140°
	42°	180°	170°
	51°	300°	280°

(2) *The rate of falling off in the sensitivity of the retina to*

color from center to periphery. To determine the falling off in sensitivity of the retina, the limen of color must be known at several points of excentricity. For this determination, the results given in Table VIII, which shows the limens of color when the brightness influence of the screen has been eliminated, best serve our purpose. They show that at 5° from the limit, the limen has been increased from three to tenfold as compared with the limen at 25°, or six to fourteenfold as compared with the limen at the center. The distance between the point 25° from the center, and the point 5° inwards from the limit averages for all colors about 10°. It is readily seen that the sensitivity falls off much faster from the point 25° from the center to 5° from the limit than it does from the center to the 25° point. At the point 3° inwards from the limit, the limen ranges from 145° of color, in the case of blue and green, to 150° of color, in the case of yellow and red. It is from this point that the sensitivity falls off with extreme rapidity. As was mentioned earlier in the discussion (see p. 105), a change in the fixation of 1° peripheralwards causes an increase in the limen of 65° or more, an increase that represents a greater lessening of sensitivity in 1° of excentricity than there was in the first 25° from the fovea.

Values of the limen for all colors with gray screens of the brightness of the color at 0° and 25° from the center, and 5°, 3°, 2°, and 1° from the limit are shown in Table VIII. They were determined in the temporal meridian of Observer *A* and are selected as typical. An equal zone of rapidly decreasing sensitivity was found on the nasal meridian also in every case where the limit of color sensitivity occurred within the range of our apparatus.

In Tables V and VI, it was shown that the limits of color are not changed more than 5° with the white and black screens from their values with screens of the brightness of the color used. The results of Table VIII show why this is so. The comparatively large amounts of induction by the white and the black screens narrow the limits so little because of the extreme rapidity with which sensitivity falls off in this zone. To narrow the limits even 3°, enough brightness must be induced, roughly speaking, to completely inhibit more than 200° of color.

TABLE VIII.

A. *Showing the rapid falling off in sensitivity of the extreme peripheral retina.*

Stimulus	Limen at 0°	Limen at 25°	Limen 5° from limit	Limen 3° from limit	Limen 2° from limit	Limen 1° from limit	Limit
Yellow	18°	35°	100°	150°	240°	330°	44°
Green	20°	40°	130°	145°	260°	345°	37°
Red	9°	17°	132°	150°	200°	320°	43°
Blue	9°	12°	130°	145°	200°	310°	53°

The following points, then, needed in our explanation of the influence of the white and black screens on the limits of color sensitivity have been established. (*a*) The white screen, which induces black, narrows the limits of sensitivity to red and yellow more than the black screen, which induces white, because neither screen narrows the limit more than 5°, and within this zone of 5°, red and yellow are inhibited by black more than by white. (*b*) The limits of blue and green are narrowed by the black screen more than by the white screen, because within this zone of 5°, as at the center, these colors are inhibited more by white than by black. But they are narrowed less by the black screen than might be expected from the inhibitive action of white found to obtain at the center, because as we go towards the periphery, the difference between the inhibitive actions of white and black decreases. And (*c*) neither screen narrows the limits for any color more than 5°, because within the zone 5° from the limits, the sensitivity falls off so abruptly from point to point that more brightness action is required to change the limits beyond this amount than either the white or the black screen induces.

We have explained the limits of sensitivity to the four colors when black and white screens are used. We have still to explain the results obtained with the gray screen. Since it causes no brightness induction, we might expect our widest limits to occur with this screen. Table V and VI, however, show that while this is true to some extent for blue and green, it is not true for red and yellow. The limits for red and yellow with the gray screen

of the brightness of the color are in each case slightly narrower than with the black screen and wider than with the white. As we are still working on this point, we do not at present feel justified in saying anything final by way of explanation. We may point out, though, that red and yellow darken in passing into the peripheral field of vision. The black screen tends to lessen this effect by contrast, and the white screen to augment it. It seems reasonable to expect, then, that the black screen, which lessens, by means of the white contrast, the amount of black füsed with these colors in darkening, would widen their limits; and that the white screen, which increases it by means of black contrast, would narrow their limits, as compared with the gray screen, which exerts no effect at all. We can speak only tentatively, however, until the amounts of brightness dealt with in each case can be more accurately ascertained.

C. *The Effect of the Induction of the Surrounding Field upon the Color Limens.*

In order to estimate the effect of the induction of the surrounding field upon the limen of sensitivity to the different colors, the limens of color were determined at the center, and at 15°, 25°, and 30° of excentricity in the peripheral retina (*a*) when the surrounding field was of the gray of the brightness of the color; (*b*) when it was white; and (*c*) when it was black.

The preëxposure was in each case to the gray of the brightness of color. The limen was determined as follows: The stimulus composed of sectors of the color and the gray of the brightness of the color at the excentricity for which the limen was to be determined, was placed on the motor behind the campimeter screen. The proportions of the sectors were changed until the observer made the judgment of just noticeable color. Judgments were taken in ascending and descending series, and the average was taken as the value of the limen.

The results show that the influence of the brightness of the surrounding field upon the color limen is as follows:

1. The limen is lowest when the surrounding field is of the gray of the brightness of the color.

2. The difference in the effect of the white and black screens upon the limen increases from the fovea outwards.

3. For yellow and green the limen is highest when the field is black and the induction white, and lower when the field is white and the induction black.

4. For red and blue, the limen is highest when the field is white and the induction black, and lower when the field is black and the induction white.

5. The difference in the effect of white and black screens on the limens is not so great as one at first thought might be led to expect from the results obtained by the objective mixing of white and black with color in the central retina.

The results for Observer *A* are given in detail in Table IX.

D. *Explanation of the Effect of the Induction of the Surrounding Field upon the Color Limens.*

We have, then, the following facts to explain: (1) The limen of sensitivity to color is lowest when the surrounding field is of the gray of the brightness of the color. This is what should be expected, because in case of this screen there is no induction present to fuse with the color sensation, and to affect the limen of sensitivity. (2) The difference in the effect of the white and black screens increases from the fovea outwards. This is because the sensitivity of the retina to brightness contrast increases from the fovea outwards, as the table for the amounts of induction shows. More white and black, then, are induced, and as our results with objective mixing show, the greater are the amounts of white and black mixed with color, the greater is the difference between the inhibitive actions of equal amounts of each.[26] (3) The limen of sensitivity to yellow and green is high-

[26] A rough demonstration of this can be easily made as follows. Set up two discs, of blue for example, side by side on color-mixers. Add a small sector of white to the one and an equal sector of black to the other, and observe the apparent saturations of each. Repeat the observation several times, each time increasing the sectors of black and white by equal amounts. It will be observed that the difference in the apparent saturations of the equally saturated discs becomes greater and greater, until at 180° the disc to which white was added appears almost colorless while the disc to which black was added is still a well-saturated dark blue.

est when the surrounding field is black, and lower when the surrounding field is white. This is in accord with the general law of the inhibitive action of white and black on color. That is, since color is inhibited less by black than by white, we should expect in terms of the law that the limen of color would be lower with the white screen which induces black than with the black screen which induces white. The limens obtained for yellow and green present no exception to this law. (4) The limens for red and blue are highest when the surrounding field is white, and lower when the surrounding field is black. But this is in apparent contradiction to our general law of the relative inhibitive action of white and black upon the colors. An explanation of why we have this apparent contradition in case of red and blue and not in case of yellow and green may be readily found, however, in the relative amounts of contrast induced by the white and black screens across these colors. Table XII (p. 142) shows the amount of contrast that is induced by the white and the black screens across the grays of the brightness of the colors. As we have already mentioned, the white screen induces more black across the grays of the brightness of red and blue, than of yellow and green; the black screen induces more white across the grays of the brightness of yellow and green, than of red and blue. For example, Observer *A* estimated the amount of black induced by the white screen at 25° in the horizontal temporal meridian as 135° for yellow, and 155° for green; and the amount of white induced by the black screen as 110° for yellow, and 60° for green. There is, then, less white induced across these two colors by the black screen than there is black induced by the white screen. In spite of this, however, the greater inhibitive power of this smaller amount of white is sufficient to raise the limen of sensitivity to yellow and green slightly higher than it is raised by the less inhibitive power of the larger amount of black. For red and blue, on the other hand, the black induced by the white screen is estimated as 230° for red, and 290° for blue; while the white induced by the black screen is estimated as only 28° for red and only 12° for blue. In these cases there is a very much greater amount of black induced than of white.

And this very much greater amount of black is sufficient to raise the limen of sensitivity to the colors with which it is fused higher than it is raised by the very small amount of white, in spite of the fact that when equal amounts of black and white are mixed with a color, its saturation is inhibited much more by white than by black. (5) The difference in the effect of white and black screens on the limens is not so great as one at first thought might be led to expect from the results obtained by the objective mixing of white and black with color in the central retina. This may be explained as follows. (1) The relative amounts of white and black induced upon the different colors by the screens vary greatly. We have thus not a simple case of a difference in the inhibitive action of equal amounts of black and white. In case of yellow and green, for example, there is so much more black induced than white that the white raises the limen very little more than the black. And in case of red and blue, the amount of black induced is so very much in excess of the white that the limen is raised even more by the black than by the white. It is not raised much more, however, (even less than the excess for white in case of yellow and green), because (*a*) the excess of black induction is not sufficiently large greatly to overweigh the superior inhibitive power of white; and (*b*) the difference between the inhibitive powers of white and black is high for red and blue, especially for blue. (2) The difference in the inhibitive power of white and black on colors decreases from the center to the periphery of the retina. Thus not so great a difference is found in the limens for white and black screens in the peripheral retina as one might be led to expect from the amounts of induction present. An inspection of the table shows that the difference in the limens for the white and black screens increases from the center towards the periphery, but this increase caused by the greatly increased amounts of induction[27] is not so great as it would have been, were there no decrease in the difference in the inhibitive power of white and black on the different colors.

[27] It has already been shown, footnote, p. 121, that the greater are the equal amounts of white and black added to color, the greater will be the difference in the inhibitive actions exerted by these equal amounts.

TABLE IX

A. *Showing the limens of color sensitivity with screens of white, black, and gray of the brightness of color.*

Stimulus	Point on horizontal temporal meridian at which limen was taken	Limen with screen of gray of brightness of color	Limen with white screen	Limen with black screen
Yellow	0°	18°	22°	28°
	15°	22°	25°	35°
	25°	35°	50°	65°
	30°	50°	80°	95°
Green	0°	20°	22°	28°
	15°	27°	30°	35°
	25°	40°	50°	75°
Red	0°	9°	13°	10°
	15°	9°	19°	15°
	25°	17°	30°	23°
	30°	25°	50°	29°
Blue	0°	9°	17°	10°
	15°	10°	25°	12°
	25°	12°	35°	18°
	30°	20°	40°	30°

We have explained the effect of the induction of the surrounding field on the limits of color sensitivity, and on the limens of sensitivity. As we have said, the effect on the limit takes place in the extreme peripheral retina; the effect on the limen has been measured in the more central regions of the retina,—at 0°, 15°, 25°, and 30° of excentricity. We have remaining to compare the effect of the induction of the surrounding field in the extreme peripheral retina, as estimated by the limit, with its effect in the more central regions, as estimated by the limen, and in turn to determine how both sets of effects harmonize with our law of the inhibitive action of brightness on the colors. The comparison of the results obtained by the two methods for each of the colors is as follows:

1. For yellow, the limen of sensitivity was lower with the white screen but its limit was wider with the black screen. The effect of the screen upon the limen for this color is in accord with our general law of the relative inhibitive action of white and black upon the colors; and the effect of the screen on the limit

is in accord with its exception formulated for the extreme peripheral retina; that is, that in the region 5° from the limit for yellow, black inhibits yellow more than white does.

2. For green, the limen was lower and the limit was wider with the white than with the black screen. The effect of the induction of the screens, then, on both limens and limits, is in accord with our general law.

3. For red, the limen was lower and the limit was wider with the black than with the white screen. The effect of the induction of the screens on the limen is not in accord with our general law that white inhibits color more than black; however, the exception is readily explained by the much greater amount of black than of white that is fused with the color sensation by the induction of the screens. The effect on the limit is in accord with our exception to this law formulated for the extreme peripheral retina; that is, that within the region 5° from the limit of sensitivity to red, black inhibits red more than white does.

4. For blue, the limen was lower with the black screen, but the limit was wider with the white screen. The effect of the induction of the screen on the limen is not in accord with our general law, but the exception may be explained, as in case of red, in terms of the very much greater amount of black induced by the white screen than of white induced by the black screen. We have here, however, an apparent paradox with regard to the limits. That is, since the law of the relative inhibitive action of white and black is the same at the limit for blue as it is at the center, we might expect that if the black induction was sufficiently in excess of the white to make the limens higher for the white screen than they were for the black, it would also correspondingly make the limits narrower for the white screen than for the black. The reverse, however, it will be remembered, was true. The reason for this lies in the fact often mentioned previously that blue lightens in the periphery, so that near its limit of sensitivity it is not in so much greater contrast to the white screen than to the black screen as it is in the center. For example, for Observer *A* the brightness of blue in the periphery

equalled gray No. 28. In the periphery, then, the amount of white induced by the black screen is sufficient to inhibit the blue sensation more than it is inhibited by the amount of black induced by the white screen. It may be mentioned, however, that the difference between the limits for blue with the white screen and with the black screen is smaller for all observers used than is the difference between the limits with these screens for any other color with which we worked (see Tables V and VI, p. 114).

3. *The Brightness of the Preëxposure.*

When making the color observation in the peripheral retina, the observer is given a short period of preparation before the stimulus is exposed, in which to obtain and hold a steady and accurate fixation. This introduces the factor of preëxposure, for during this period of preparation, the area which is to be stimulated by color receives a previous stimulation. It seems strange to the writer that this factor, which exerts a greater influence over the extent of color sensitivity than any we are examining, with the possible exception of large changes in the general illumination, should have been so generally overlooked in the work of earlier investigators. It has always been considered a sufficient precaution to eliminate all color from the preëxposure. This, however, is not enough. It should also be of the same brightness as the color by which the eye is to be stimulated. If not, it gives an after-image which mixes with the succeeding color sensation and both reduces its saturation and modifies its color tone.[28] If the preëxposure is lighter than the stimulus color, it adds by after-image a certain amount of black to the succeeding color impression; if darker, it adds a certain amount of white. Since white inhibits color more than black, the effect of a dark preëxposure is to reduce the sensitivity to color more

[28] This action takes place apparently at some physiological level posterior to the seat of the positive, negative, and contrast color processes commonly supposed to be located in the retina. (See Ferree and Rand. An Experimental Study of the Fusion of Colored and Colorless Light Sensation: The Locus of the Action. Journ. of Philos. Psychol. and Scientific Methods, 1911, VIII., pp. 294-297.)

than the effect of a light preëxposure.[29] But since both white and black as after-effect reduce the sensitivity to color, the eye is rendered more sensitive when no after-image is given, that is, when the preëxposure is of the same brightness as the color. The preëxposure should, therefore, be to a gray of the brightness of the color. No brightness after-image will be added to the succeeding color impression to modify either its saturation or its color tone. Even closing the eye, as is frequently done before stimulating, is equivalent to giving a black preëxposure.

No thought apparently was given by previous experimenters to the intense after-effect which follows the exposure of the eye to a brightness quality differing from that of the stimulus. Hess,[30] Fernald,[31] and Thompson and Gordon,[32] it is true, covered the stimulus before exposure with a card matching in quality the campimeter screen, but since the campimeter screen was not always of the same brightness as the color used for the stimulus, this by no means ruled out the effect of preëxposure. The motive of each of these experimenters seems to have been to standardize the observation for the effect of preëxposure, but no notion of its action sufficiently clear to guide them in formulating their technique seems to have been entertained. Since the action of the preëxposure is by way of arousing a brightness after-image, it is obvious that the preëxposure card should, as stated above, be matched in brightness to the stimulus color rather than to the screen.

In the articles, *"Colored After-Image and Contrast Sensa-*

[29] A very striking demonstration of the effect of preëxposure upon the sensitivity of the retina to color can be made for class or lecture room purposes as follows. Mount a sheet of the blue paper of the Hering series on cardboard. Cover one-half of another sheet of cardboard of the same size with white of the Hering series of papers, the other half with velvet black. Place this card immediately in front of the first card and fixate its center for 10 or 15 seconds. Remove and observe the comparative effect of the white and black preëxposures thus obtained upon the color impression gotten from the blue surface.

[30] Hess, C. loc. cit.

[31] Fernald, G. M. Psychol. Rev., 1905, XII., p. 394; Psychol. Rev. Monog. Sup., 1909, X., No. 42, p. 17.

[32] Thompson and Gordon. A Study of After-images on the Peripheral Retina. Psychol. Rev., 1907, XIV., p. 123.

tions from Stimuli in Which No Color Is Sensed,"[33] and *"The Fusion of Colored with Colorless Light Sensation.—The Physiological Level at Which the Action Takes Place,"*[34] the effect of the after-image due to previous brightness exposure upon color sensitivity has already been shown for both central and peripheral retina. The general fact need not further be dwelt on here. We do, however, need to show why in the peripheral retina the short preëxposure which takes place while the eye is obtaining a steady fixation has so much effect upon the color stimulation immediately following. Two reasons are found for this. (*a*) The peripheral retina is extremely sensitive to short stimulation. While some slight variation is found at different angles of excentricity, the peripheral after-image reaches in general its maximal intensity with two or three seconds stimulation. This amount of time is usually consumed in obtaining fixation, hence in each observation there is fused with the color sensation about as strong a brightness after-image as can be aroused. For this reason alone, it is readily seen why the brightness of the preexposure is of so much greater consequence in the peripheral retina than it is in the central retina, where the maximal strength of the after-image is obtained with from forty to sixty seconds stimulation. (*b*) There is apparently no latent period in case of the peripheral after-image. It flashes out at full intensity immediately upon the cessation of the stimulus. Thus, there is no possibility of escaping the full effect of the brightness after-image upon the stimulus color, as might happen in the central retina, where the latent period obtains, if there were a very short exposure to the stimulus color.

If when working with the campimeter, for example, a black card is used to cover the stimulus-opening during the period of preparation, an intensive white after-image is aroused which

[33] Ferree and Rand. Psychol. Rev., 1912, XIX., pp. 195-239.

[34] For abstract of the article, see Journ. of Philos. Psychol. and Scientific Methods, 1911, VIII., pp. 294-297. The article will soon be published in full. See also Ferree, C. E. Tests for the Efficiency of the Eye Under Different Systems of Illumination and a Preliminary Study of the Causes of Discomfort. Transactions of the Illuminating Engineering Society, 1913, VIII., pp. 40-60.

fuses with the succeeding color sensation, strongly reducing its saturation. If, on the other hand, a white card is used, a black after-image is obtained, which, according to our law of the action of the achromatic sensation upon color, has less effect than the white after-image upon blue and green, and also upon red and yellow if the after-image is sufficiently strong to narrow the limits to red and yellow more than 5°. In each case, the intensity of the after-image will in part depend on the brightness of the subsequent color exposure, the projection field. The after-image due to preëxposure to white will be more intensive when blue than when yellow forms its projection field. The after-image from black will be more intensive when projected on yellow or green than on blue or red. If, however, a gray card of the brightness of the stimulus color be used as preëxposure, there will be no after-image to modify the color sensation. The only brightness change acting upon it will be due to the slight adaptation to this gray during the short time of preëxposure.

The method, then, of eliminating the effect of preëxposure consists in making it of the brightness of the color to be used as stimulus. And in case the brightness of the color alters in passing from the center to the periphery of the retina, the brightness of the preëxposure must be correspondingly altered. For example, at standard illumination, Hering Gray No. 41, or its equivalent should be used for preëxposure to blue when the central retina is investigated. But for the peripheral retina, a much lighter gray should be used because in this region blue lightens by an amount depending upon the excentricity of the stimulation and in part upon individual variation.

A. *Effect upon the Limens of Color and upon the Limits of Color Sensitivity.*

To test the importance of preëxposure, two methods of measurement were employed. In the first, the limen of color was obtained at 0° and at 35° on the temporal meridian, when the screen was of the gray of the brightness of color, and the preëxposure was in turn to the same gray, to white, and to black. In the second method, the limits of color sensitivity were investigated under the same conditions of campimeter

screen and preëxposure card. The results for Observer *A* are recorded in Table X and in rows 1, 4, 7, 10 of Table XI. They show in every case, (*a*) that the limen is raised and the limit is considerably narrowed when the preëxposure is not to the gray of the brightness of the color, that is, when it gives a brightness after-image; and (*b*) that the limen is higher and the limit narrower when the preëxposure is to black and its after-image is white, than when the preëxposure is to white and its after-image black.[35] This is in accord with the law of the

[35] There is one exception to this statement. The limen for blue at O° for both white and black preëxposures is 13°. The following reasons may be given for this. (a) It is one of the fundamental laws of brightness after-images that the intensity of the after-image depends in part upon the brightness relation of stimulus to projection field. When the brightness difference between the stimulus and the projection field is small, a weak after-effect is obtained; when it is greater, a more intensive after-effect is obtained. Blue, as aroused in the central retina, is very near to black in brightness, and very far removed from white. We should then expect a very much more intensive after-effect of the exposure to white than to black when the projection field is blue. (b) The brightness relation of the surrounding field to the preëxposure also exerts an effect on the intensity of the after-mage given by the preëxposure. When the surrounding field differs in brightness from the preëxposure, contrast is induced. This contrast quality in turn also gives an after-image which mixes with and modifies the after-image given by the preëxposure. When the surrounding field is of the gray of the brightness of blue, for example, and the preëxposures are in turn white and black, the influence of the surrounding field is to make the after-image of white stronger than that of black. That is, when the preëxposure is white, this white is strongly intensified by contrast with the surrounding field of dark gray, and in consequence the black after-image is strongly intensified. But when the preëxposure is black, little intensification results by contrast with the surrounding field and little effect is had on the after-image. Both of these influences, then, tend to cause much more black to be added to a blue stimulus in the central retina as a result of preëxposure to white than white to be added as a result of preëxposure to black. The effect of this excess of black, as is shown by the table, is to raise the limen for blue for the white preëxposure as much as it is raised by the black preëxposure; in other words, to make the limens equal. At 35° in the periphery, however, the limen of blue is seen in the table to be higher when the preëxposure is to black and the after-image white, than when the preëxposure is to white and the after-image black. We have here a different case. The difference in the effect of white and black preëxposures at O° and at 35° is due to the fact that at O° blue is very dark while at 35° in the periphery it has lightened until its brightness equals No. 35 gray. In the latter case (a) there is less difference than there was at O° between the brightness relations of the stimulus to

action of brightness upon color and holds for all colors used. It might be expected from the exception to this law, mentioned on page 116, that the limits for red and yellow would be narrowed more by the black after-image than by the white. This is not found to be true because the effect of each after-image is sufficiently strong to narrow the limits of red and yellow more than 5°, and thus to carry the limits for these colors outside of the zone in which they are inhibited more by black than by white.

B. *Combined Effect of Surrounding Field and Preëxposure upon the Limits of Color Sensitivity.*

The effect of preëxposure upon color limits was also investigated when white and black screens were used. The results obtained are of interest in two regards. (*a*) They show under these typical conditions in what way and to what extent the inductive action of the screen combines with the effect of preëxposure to modify the limits of color. (*b*) They help to explain some of the conflicting results obtained by previous investigators who did not carefully standardize their observations with reference to the effect of preëxposure and surrounding field. A few points may be noted in advance of the tables showing the combined action of preëxposure and surrounding field upon the extent of color sensitivity. It is obvious that when the campimeter screen is either white or black and the preëxposure is to the same brightness quality, there will be no inductive

the white preëxposure and of the stimulus to the black preëxposure, and consequently less difference between the intensities of the after-images from these preëxposures; and (b) there is less difference than there was at O° between the brightness relations of the surrounding field, which is of the brightness of blue at the point at which we are working, to the white preëxposure and of the surrounding field to the black preëxposure, and for this reason also, less difference between the intensities of the after-effect of the contrast induced by the surrounding field upon these preëxposures. For both reasons, therefore, the after-image from the white preëxposure at 35°, when projected on blue, is not so much more intense than the after-image from the black preëxposure, as it was at O°. At 35°, then, in these experiments the white after-effect due to preëxposure to black is sufficiently intensive to raise the limen of blue higher by virtue of its greater inhibitive power than it is raised by the black after-image due to preexposure to white.

action by the screen upon the preëxposure either to intensify or to weaken it. In this case both preëxposure and screen will add the same brightness quality to the stimulus color, the former by contrast, and the latter by after-image. The effect of this action upon the color limits is shown in Table XI, Column 4, rows 2, 5, 8, 11; and column 5, rows 3, 6, 9, 12. If, however, the preëxposure and the screen are different in quality, their action may be either antagonistic or supplementary, depending upon the brightness relations between the screen and the preëxposure, on the one hand, and between the screen and the color sensation fused with the after-image of preëxposure on the other. For example, if a black preëxposure and a white campimeter screen are used, the white screen will intensify the blackness of the preëxposure by contrast but will tend to darken the fusion of color sensation and white after-image, and thus will lessen the action of the latter upon the color. This effect is shown in Table XI, in column 4, rows 3, 6, 9, 12; and column 5, rows 2, 5, 8, 11. If, however, the preëxposure is black. and the campimeter screen is the gray of the stimulus color, the

TABLE X.

A. *Showing the effect upon the color limens of preëxposure of the gray of the brightness of the color used, of white, and of black.*

Stimulus	Surrounding field	Preëxposure	Limen at 0°	Limen at 35°
Yellow	gray no. 2	gray no. 2	18°	83°
		white	35°	105°
		black	45°	125°
Green	gray no. 8	gray no. 8	20°	100° [38]
		white	33°	155°
		black	40°	180°
Red	gray no. 24	gray no. 24	9°	90°
		black	13°	135°
		white	20°	148°
Blue	gray no. 41 at 0°	gray	9°	30°
	no. 35 " 35°	white	13°	40°
		black	13°	43°

[38] As green has a narrow zone of visibility, the limen was taken at 30°.

screen will intensify the blackness of the preëxposure by contrast, but will lighten the fusion of stimulus color and white after-image, thus will add to the action of the latter upon the color. This effect is shown in Table XI, columns 4 and 5, rows 1, 4, 7, 10.

TABLE XI.

A. *Showing the combined effect of campimeter screen and preëxposure upon the limits of color sensitivity.*

Stimulus	Campimeter screen	Limit with gray preëxposure of the brightness of the color	Limit with white preëxposure	Limit with black preëxposure
Yellow	gray no. 2	44°	40°	38°
	white	42°	42°	43°
	black	45°	43°	40°
Green	gray no. 8	37°	35°	31°
	white	36°	30°	25°
	black	34°	36°	25°
Red	gray no. 24	43°	38°	37°
	white	42°	38°	39°
	black	44°	43°	38°
Blue	gray no. 28	53°	42° [37]	42° [37]
	white	50°	42° [37]	48°
	black	49°	51°	42° [37]

Having seen from Tables X and XI the effect of preëxposure and the combined effect of preëxposure and surrounding field upon the limen and the limits of color, we may turn our attention to a third point of interest; namely, the explanation of some of the differences between our results and those obtained by earlier investigators in terms of the different conditions of preexposure used. As Hess and Fernald alone have stated their conditions of preëxposure, we shall have to limit our discussion to them. Hess wished to find the comparative limits of color sensitivity. He attempted to standardize the intensity and the brightness of the stimuli used, and worked with white, black, and gray campimeter screens. The eye of the observer followed

[37] For the explanation of this decided narrowing of the limit for blue, see footnote, p. 108.

a moving fixation-point while the stimulus was exposed from time to time. In every case, the stimulus was covered by a card of the same brightness and quality as the screen. He turned the gray screen toward or away from the source of light until its brightness was such that the color disappeared in the periphery into a gray of the brightness of the screens. He thus worked with screens of the gray of the brightness of the color, of white, and of black, and with preëxposures of the same brightness as the screens. In only one of these cases, namely, the first, has he eliminated the effect of preëxposure. He found that for every color, the limit of sensitivity was widest with the gray screen, narrower with the black, and narrowest with the white. His results are in contradiction to ours with regard to the influence of these screens, when the factor of preëxposure is eliminated (see p. 113). They are, however, very nearly confirmed by the results we obtained when the preëxposure was of the same brightness as the screen (See Table XI). Had our illumination been slightly less, and consequently the induction from the white screen greater, our results would have been very similar to those of Hess.

Fernald, working with a white and a black background and using preëxposures to match, obtained results that are similar to those of Hess for all colors except red, and even in this case the exception is only apparent. She says: "All the colors except the reds are perceived at a greater degree of eccentricity with the dark than with the light background. Red is seen as red to about the same degree of eccentricity with the dark as with the light background, but is seen as yellow or orange with the dark background at the same points at which it is seen as colorless with the light background."[38] The latter part of the quotation shows that the exception to Hess in case of red was due rather to a difference in the method of measurement than to a difference in result. She recorded as the limit of color the point at which the sensation took on any trace of a foreign quality. Although the red stimulus appeared as red-yellow in the periphery with the black screen, there was some red in the

[38] Fernald, G. Psychol. Rev. Monog., 1909, X, p. 23.

sensation received from it at a greater angle of excentricity with the dark than with the light screen.

As was said above, the conclusion of Hess and of Fernald that the colors have wider limits with the black than with the white screen, is confirmed by our work at certain illuminations when white and black preëxposures are used. But, since we do not obtain similar results when the influence of preëxposure is eliminated and the effect of the brightness of the field determined in isolation from this factor, we maintain that their results were due to brightness conditions not connected with the surrounding field, but with the preëxposure. Our contention is that many of the conflicting conclusions concerning the effect of background upon color limits have resulted from ignorance of the important factor of preëxposure. Comparative color limits can be obtained with any screen only when the preëxposure is to the gray of the brightness of the stimulus. This principle was used by Hess in his work with the gray screen, but apparently without a definite purpose and without knowledge of its importance.

4. *The General Illumination of the Retina.*

The effect of change of illumination was forced upon our attention early in the investigation of the factors that influence the color sensitivity of the retina. For example, in preliminary work done by the writer on a well-lighted porch on Long Island, changes in color tone were reported, when certain colors were compared in the central and in the peripheral retina, that are not found at all under the more intensive illumination of our optics-room, when neither of the curtains is drawn; and the peripheral limits of color were narrower by 5° to 12°. Furthermore, on a dark day, it was found that the limits of stimuli exposed through an opening in a white screen were reduced by about 4° as compared with the limits taken on a bright day The change was less considerable with black and gray screens. The change in color tone was most conspicuous in case of green.[39] On dark days the green stimulus appeared as a pale unsaturated blue before becoming colorless in passing from the center to the periphery of the retina. This zone of blue was from 7° to 23°

[39] The green of the Hering series was used.

wide in different meridians of the retina with both white and black screens, but was wider with the black than with the white screen. On a sunny day, on the other hand, with the white screen green passed into bluish-green, then directly into gray, except in case of the upper regions where it appeared blue throughout a zone of about 4° in width. With the black screen, the blue zone was found only in the upper and temporal regions of the retina. The transition of green to yellow in the periphery that is generally reported in the literature was found in these experiments only when the gray screen was used. Yellow showed a color change that varied in amount with the degree of the general illumination. On a bright day, it appeared reddish-orange with the white screen. On a cloudy day, it was seen in the extreme periphery as a dark saturated red.

Working in our optics-room we found also that results taken on one day could not at all be duplicated on the following day. When the work was carried on under the most favorable conditions without special means of controlling illumination, namely, on bright days only, differences of 5° or more were found when the white screen was used. This necessitated a long series of observations if legitimate averages were to be obtained. Such a procedure is at best a poor makeshift and is besides of great disadvantage in many problems that come up in the work on color sensitivity. Particular instances of this may be found in investigations in which it is required to work in the region lying just within the limits of sensitivity, and in work on the after-images of stimuli in which no color is sensed. In the latter case the experiment requires that the stimulus be exposed just outside the limits of sensitivity determined with a given brightness condition, and that the observer should not be aware of the nature of the stimulus. In order to fulfill these requirements the experimenter must know the limits obtaining with a given brightness condition. It would be impossible to know this when the brightness conditions were subjected to the influence of changing illumination unless re-determinations were made at the beginning of each sitting and even frequently during its course. This would consume a great deal of time and would, besides,

only roughly fulfill the requirements of the problem. A further and still more important example of the disadvantage may be found in the task we had set ourselves, namely, to investigate from point to point the sensitivity of the retina to each of the principal colors for three backgrounds in at least sixteen different meridians. In this work it is obvious that unless a standard illumination were provided, all comparative work would have to be done at one sitting. This is impossible. When time is taken between observations to guard against fatigue, at least three hours is required merely to outline the limits of sensitivity for a given color with one background for only one-half of the retina. Even for this length of time there is no guarantee that the illumination has not altered. Thus at the outset of any extended investigation of color sensitivity, it is evident that without a standard illumination, results will be of little comparative value.

In order better to know our factor and the ways in which it operates, a systematic investigation of the influence of changes of general illumination was carried on in our optics-room, which is especially constructed to secure fine changes in illumination. Rough preliminary experiments showed that the primary effect of decreasing the illumination was an alteration of the amount of contrast induced across the stimulus by the campimeter screen. With the white screen, the increased induction was the most pronounced and was sufficient to cause large changes in the limits and in the color tone of the stimulus. In order to investigate this effect in detail, gradual changes of illumination covering a wide range were made by means of the curtains with which our optics-room is furnished, described on p. 86. Attention was given to the following points. (*a*) A quantitative estimate was made of the influence of change of illumination upon the brightness induction of the campimeter screen. (*b*) The effect of this induction upon the limits of color sensitivity was determined. (*c*) The limens of the colors were measured at different degrees of excentricity at different illuminations. And (*d*) the influence of change of illumination upon the effect of the preëxposure on the limens and limits of color was investigated. The degrees

of illumination chosen for comparison were the standard illumination, the method of obtaining which will be described later, and the decreased illumination mentioned above (see p. 95 and Tables I and II) for which the white-values of the stimuli were determined. Measured in foot-candles by means of the Sharpe-Millar portable photometer, the standard illumination equalled 390 foot-candles, the decreased 1.65 foot-candles.

A. Quantitative Estimate of the Influence of Change of Illumination upon the Induction of Brightness by the Surrounding Field.

The purpose of this investigation was to find out how much the induction from white and black screens[40] is affected by a change in the general illumination; and (*b*) how much induction is gotten at decreased illumination from the gray screen which matches the color in brightness at standard illumination. The induction in this latter case is caused by the change in the brightness relation between color and screens with decrease of illumination.[41] The campimeter screens served as inducing surface, grays of the brightness of the four principal colors of the Hering series both at standard and decreased illumination were used in turn as stimuli, and the amount of induction was estimated upon a measuring-disc, made up of adjustable sectors of the gray of the stimulus and white or black, according to the screen used. The measuring-disc was mounted on a motor (see p. 87 and Fig. I) which could be moved along the graded arm of the campimeter to any position from 20° to 92°. The gray stimulus was exposed through the opening of the screen in the usual manner. Two preliminary precautions were observed. (*a*) Since

[40] White and black screens are chosen because they represent the extreme cases of the effect of change of illumination.

[41] This latter determination is made to show that it is impossible to standardize the brightness of the surrounding field against the sudden and progressive changes of daylight that occur during the course of a single series of observations. These changes alter the brightness relation between the colored stimulus and the gray used as screen; therefore a match made at the beginning of a series will not hold throughout its course. For the same reason and to an equal degree the brightness relation between preëxposure and colored stimulus changes with change of illumination. It is, therefore, equally impossible to standardize the brightness of the preexposure without some means of securing a standard illumination.

the brightness of the gray stimulus plus the induction of the screen was to be estimated by means of the measuring-disc, and since the brightness-value of the stimulus and of the disc changes with the amount of light that falls upon them, it was necessary to make sure before each measurement that the same amount of light fell upon each. This precaution was all the more necessary because the stimulus had to be placed behind the screen and the measuring-disc in front. In a given position of the apparatus, one or the other was apt to be shaded. The determination was made as follows: Measuring-disc, campimeter screen, and gray stimulus were all given the same brightness-value according to determinations made under conditions about which no doubt of the equality of the illumination of each could be entertained. Each was then placed in position for the experiment, and the position of the campimeter as a whole and of its various parts was adjusted until stimulus, screen, and measuring-disc were exactly matched in brightness-value. When an exact match was obtained we were guaranteed that all three were again equally illuminated. This precaution was particularly necessary in the investigation we are discussing in this section. It was carefully observed, however, throughout the entire work. (*b*) The question arose whether brightness induction comes to its maximal value at once in the peripheral retina. A determination of the intensity curve of the contrast sensation was accordingly made at various points in the peripheral retina. It showed that contrast increases strongly for the first few seconds of stimulation. For this reason it was found to be necessary to make the judgment concerning the amount of induction of the screen, just as long after the induction had commenced as was done in the experiments to determine color sensitivity. In the color experiments an interval has to be allowed before the stimulus is exposed during which the observer obtains a steady fixation. During this interval of preëxposure, the eye is being stimulated by the campimeter screen and by the card which covers the stimulus. To prevent the preëxposure card from giving a brightness after-image which would fuse with and modify the sensation immediately following, it should be chosen of a gray of the

brightness of the color. In the same way, an interval had to be given in which to secure steady fixation when the amount of brightness induction was being measured. In order, then, to have the judgments made in each case the same length of time after induction had begun it was necessary only to make the intervals of preëxposure of equal duration and to require that the judgments of each kind be made directly at the end of the preëxposure. In the case of the color experiments, the signal for the making of the judgment is the withdrawal of the preëxposure card and the exposure of the stimulus. For the judgments of induction, however, in which case the stimulus was the gray of the brightness of the color, it is obvious that no preëxposure card was needed, for preëxposure and stimulus were required by the conditions of the experiment to be the same. In this case, a word-signal had to be given to indicate the termination of the preëxposure interval and the instant at which the judgment was to be made.

Results when white and black screens were used.—Observing these precautions as to the equality of the illumination of stimulus, screen, and measuring-disc, and as to the length of time the induction had had in which to increase before the judgment was made, measurements were taken of the induction by white and black screens across grays of the brightness of the four principal colors at the illumination used. These measurements were made at various points of excentricity on the retina, and for both standard and decreased illuminations. The determination of the equality point between the stimulus and the measuring-disc was made as follows: The size of the white or black sector of the latter was changed until a preliminary judgment of equality was made. Then the j. n. d. on either side of this point was determined both by ascending and by descending series and an average of the results was taken as the value of the induction. Measurements were taken at 25° and at 40° on the temporal meridian, and at 55° and 70° on the nasal. The conditions at the nasal 55° were very similar to those at 25° on the temporal side. The measurements at 70° nasal were midway in value between those at 25° and at 40° on the temporal. The 40° point is very near the limits of color sensitivity in this meridian, and the induction here is very great. For one ob-

server, the darker stimuli appeared black at this point, when the white background was used. In such cases, the difference between the induction at standard and at decreased illumination is more clearly shown by the observations made at 25° temporal meridian and at 55° and 70° nasal meridian than at 40° temporal. We have, however, chosen for two reasons to present in the following table only the results obtained in the temporal meridian. (*a*) The results obtained in this meridian demonstrate sufficiently well all the facts that need be taken into consideration. Space will not, therefore, be given to the results for both meridians. (*b*) The second point of our problem requires us to correlate the increased amount of induction caused by a given decrease of illumination with the change in the color limits it produces. The limits of color sensitivity can be more easily investigated in the temporal meridian because the sensitivity to some colors extends in the nasal region beyond the 92° point, which is the limit of measurement for the apparatus we used. This is true in particular in case of Observer *C* as may be seen in Table VI. Both purposes of the investigation are, then, better satisfied by results obtained in the temporal meridian.

The results show in general the following facts.

(1)The amount of induction increases with the distance from the fovea.

(2) The amount of induction increases with decrease of illumination.[42]

(3) The amount of induction from the white screen is greater than that from the black screen.[42a]

(4) The amount of increase of induction at decreased illumination is greater in case of the white screen than in case of the black screen.

(5) The white and black screens induce most across the stimuli that are farthest removed from them in brightness, and least across those which are nearest to them in brightness. That

[42] This statement is meant to apply only to the range of illumination worked with. The induction was not measured when the illumination was very low, nor when it was very intensive.

[42a] An exception to this statement of result occurs in case of gray No. 2 at 40°. This stimulus is so near to white in brightness that the induction across it, according to the principle stated in (5) above, is greater for the black screen than for the white.

is, the white screen induces more black across the gray of the brightness of blue than across the gray of the brightness of yellow; the black screen induces more white across the gray of the brightness of yellow than across the gray of the brightness of blue.

Results are given in detail in Tables XII and XIII. Table XII gives the results for observer *A* taken on the temporal meridian, and Table XIII, the results for Observer *C* for the same meridian. There is some difference in the amount of induction reported by the different observers, but since the preceding general statement of results is clearly borne out in every case, it is not deemed necessary to give space to results from all the observers used. In these tables, column 1 gives the degree of excentricity at which the observation was made; columns 2, 3, and 4, show respectively the stimulus used, and the amounts of induction from the white and from the black screens at standard illumination. Columns 5, 6, and 7, give the same data for decreased illumination.

TABLE XII.

A. *Showing the amount of contrast induced by the white and the black screens at standard and decreased illumination upon the grays of the brightness of the colored stimuli at standard and at decreased illumination.*[43]

Fixation	Standard illumination			Decreased illumination		
	Stimulus (gray of brightness of each of the four colors at standard illumination)	Amt. induction of white screen	Amt. induction of black screen	Stimulus (gray of brightness of each of the four colors at decreased illumination)	Amt. induction of white screen	Amt. induction of black screen
25°	gray no. 2	Black 135°	White 110°	gray no. 2	Black 220°	White 170°
	gray no. 8	" 155°	" 60°	gray no. 6	" 270°	" 80°
	gray no. 24	" 230°	" 28°	gray no. 41	" 320°	" 40°
	gray no. 37	" 290°	" 12°	gray no. 20	" 330°	" 30°
40°	gray no. 2	" 200°	" 300°	gray no. 3	" 320°	" 360°
	gray no. 8	" 300°	" 132°	gray no. 5	" 360°	" 180°
	gray no. 24	" 360°	" 60°	gray no. 50	" 360°[44]	" 0°
	gray no. 29	" 360°	" 28°	gray no. 13	" 360°	" 100°

[43] It is obvious that the method used in this and the following tables of expressing the amount of brightness induction gives an underestimation.

TABLE XIII.

Observer C.

25°	gray no. 2	Black 70°	White 55°	gray no. 2	Black 130°	White 70°
	gray no. 8	" 84°	" 48°	gray no. 6	" 155°	" 59°
	gray no. 24	" 93°	" 30°	gray no. 40	" 187°	" 45°
	gray no. 37	" 160°	" 15°	gray no. 17	" 244°	" 22°
40°	gray no. 2	" 110°	" 200°	gray no. 3	" 216°	" 340°
	gray no. 7	" 142°	" 160°	gray no. 4	" 230°	" 320°
	gray no. 24	" 180°	" 95°	gray no. 50	" 360°"	" 0°
	gray no. 29	" 214°	" 35°	gray no. 7	" 300°	" 108°

Results when the gray screen matching the colored stimulus in brightness at standard illumination is used. It was necessary to perform the experiments bearing on this point at decreased illumination only. For them the campimeter screens which matched in brightness the four principal colors of the Hering series at standard illumination served as inducing surfaces. For

Suppose, as is shown in Table XII, that No. 24 Hering gray has been darkened by induction until it matches in brightness a disc made up of 230° of black and 130° of the No. 24 gray. The amount of induction is greater than is represented by the 230° of black because the induction has not lessened the amount of light coming to the eye from the gray paper while the addition of 230° of black to the measuring-disc has cut off approximately 2/3 of the light coming from the gray paper. That is, in the one case enough black has been added by induction to reduce 360° of No. 24 gray to the given point in the brightness scale, while in the other enough black was added by direct mixing to lower only 130° of No. 24 gray to this point in the scale. Moreover, the underestimation will be increased by this method of measuring in proportion as the amount of induction is increased because the greater the induction is the more black and the less gray will have to be used in the measuring-disc. All that can be said accurately is that a certain gray darkened or lightened by induction matches in brightness a gray made up of a certain amount of the given gray plus a certain amount of black or white. The exact amount of the induction can not be separated out. Further just because the brightness added by contrast does not alter the amount of light coming to the eye while the brightness added in any method of measurement does change this amount of light, the writer knows of no way by which an exact expression can be obtained. The method she has used, however, does serve as a means of comparing the amounts of induction occurring under different conditions sufficiently accurately for her purpose at this point.

" The gray No. 50 was in reality rendered blacker by the inductive action of gray No. 24 than the Hering black we used on the measuring-disc. A match thus could not be attained with black 360° as the table indicates.

the contrast surfaces, grays of the brightness of these colors at decreased illumination were chosen. The methods of measuring, precautions in working, parts of the retina investigated, etc., were the same as in the preceding determinations. The following general statement of results may be made.

1. At the 25° point the brightness of yellow was found not to have changed at all with the decrease of illumination produced by changing the illumination from the value selected as standard to the value selected for the comparison; the brightness of green lightened by an amount equal to the difference between No. 8 and No. 6 of the Hering series of grays; red darkened by an amount equal to the difference between No. 24 and No. 40; and blue lightened by an amount equal to the difference between No. 32 and No. 20. The amount of induction by the gray screen of the original brightness of the color upon the gray stimulus of the brightness of the color as altered by the decreased illumination, expressed in terms of Hering white and black, was for yellow 0°, for green 60° of white, for red 27° of black, and for blue 20° of white.

2. At the 40° point, the yellow darkened by an amount equal to the difference between No. 2 and No. 3 of the Hering grays; green lightened by an amount equal to the difference between No. 8 and No. 5; red darkened by an amount equal to the difference between No. 28 and No. 50; and blue lightened by an amount equal to the difference between No. 28 and No. 13. The amount of induction produced by these changes was for yellow 280° of black, for green 130° of white, for red 360° of black, and for blue 60° of white. These results are shown in detail in Table XIV.

(*B.*) *The Effect of These Amounts of Induction upon the Limits of Color Sensitivity.*

In order to obtain an estimate of the range of effect upon the limits of color sensitivity of the induction of the screens at standard and at decreased illumination, the breadth of the color zones was determined at both illuminations (*a*) when white and black served in turn as campimeter screens; and (*b*) when a gray matching the color in brightness at standard illumination was

TABLE XIV.

A. *Showing the amount of contrast induced at decreased illumination on grays of the brightness of the colors at decreased illumination by the gray screens matching the colors in brightness at standard illumination.*

Fixation	Stimulus	Screen	Amount of Induction
25°	gray no. 2	gray no. 2	0
	gray no. 6	gray no. 8	white 60°
	gray no. 41	gray no. 24	black 27°
	gray no. 20	gray no. 37	white 20°
40°	gray no. 3	gray no. 2	black 280°
	gray no. 5	gray no. 8	white 130°
	gray no. 50	gray no. 24	black 360° [45]
	gray no. 13	gray no. 29	white 60°

used. The preëxposure was in each case to gray of the same brightness as the stimulus at the illumination used.

Results when white and black screens were used. When the stimulus color is gotten by reflection from a pigment surface, two factors operate to give a change of result when the illumination is decreased. (1) There is a decrease in the amount of colored light coming to the eye. (2) There is an increase in the inductive action of the screen due to the change in the brightness relation of the stimulus to screen and to the increased sensitivity of the eye to brightness contrast at decreased illumination.

In order to find out how much of our results with the white and black screens should be attributed to the decrease in the amount of colored light coming to the eye produced by the decreased illumination, and how much to the increased inductive actions of the screens, the limits of sensitivity were also determined at both illuminations with the screens of the gray into which the color disappears in the peripheral retina. From the values obtained with the three screens at both illuminations, the amount of change due to decrease in the amount of colored light coming to the eye and the amount due to induction by the white and black screens were calculated as follows. (*a*) From

[45] The gray No. 50 was in reality rendered blacker by the inductive action of gray No. 24 than the Hering black we used on the measuring-disc. A match could not be thus attained with black 360° as the table indicates.

the number of degrees expressing the limits for a given color at standard illumination with a screen of the brightness of the color at that illumination was subtracted the number expressing its limit at decreased illumination, with a screen of the brightness of the color at the decreased illumination. That this gave the number of degrees the zone of sensitivity was narrowed by the decrease in the energy of the stimuli, may be said with the following qualification. If there is any influence upon color sensitivity of the local brightness-adaptation of the retina produced by the change in the general illumination, it is, of course, included in this effect. But, since this influence would have to be brought about by previous exposure to the illumination in question, it can be reduced to a minimum by guarding against an exposure to it for any considerable length of time. The effect of whatever adaptation there may be, however, can not be isolated or separated out from the above result, and the value expressing the amount the limit is narrowed by the actual decrease of the energy of colored light coming to the eye cannot, strictly speaking, be obtained. But it is probable that the adaptation effect is not sufficiently strong to influence the limits, since the sensitivity of the extreme peripheral retina falls off very abruptly from point to point. The difference, then, between the color limit obtained at standard illumination and the limit at decreased illumination, when in both cases there is no brightness induction from the screen, may be said to approximate the effect upon the limits produced by the decrease in the amount of colored light coming to the eye. (*b*) Figures can be obtained, however, from our results, which express the amount by which the zones are narrowed by the change in the inductive action of the white and black screens produced by decreasing the illumination, that are not open to theoretical questioning; for the influence of local brightness-adaptation, if there be any, is a constant for all screens at the same illumination. If then, the number of degrees which expresses the limits of sensitivity for either the white or the black screen at decreased illumination is subtracted from the number expressing the limit with a screen of the gray of the brightness of the color at this illumination, the result will rep-

resent the extent to which the limit was narrowed by the action of induction alone.

The results show in general the following facts:

1. At standard illumination, induction from the white screen narrows the limits of yellow and red; induction from the black screen narrows the limits of blue and green. The difference is in no case more than 4°.

2. At decreased illumination, the induction from the white screen narrows the limits of all the colors much more considerably than does the induction from the black screen.[46]

3. The values expressing the narrowing of the limits caused by decrease of illumination without induction, are greatest in case of those colors which undergo maximum change of brightness in passing into the periphery, namely, for blue and red.

We have shown by the results of the preceding section, that the increased induction produced by decrease of the general illumination is greater for the white screen than for the black, and, by the results of this section, that this increase is effective to the extent of narrowing the limits of sensitivity to all colors from 5° to 13° with this screen. With the black screen, the limits were narrowed from 0° to 6°. At standard illumination, the limits were narrowed only from 1° to 4° with either the white or the black screen.

Results in detail are given in Tables XV and XVI taken from the temporal meridians of the observers whose observations are recorded in Tables XII and XIII. In column 1, Tables XV and XVI, is given the stimulus. Column 2 shows the limit of sensitivity to the stimulus at standard illumination with a screen of a gray of the brightness of the color at standard illumination; column 3 shows the limit with a white screen; and column 4 with a black screen. Column 5 shows the limit at decreased illumination with a screen of the brightness of the

[46] For Observer *A* the results for green present an exception. At the decreased illumination used the green stimulus appeared bluish in the central retina. The induction of the black screen caused it to appear as a pale blue at a comparatively slight degree of excentricity. According to our definition of color limit, this point is the limit of green. It is, however, obvious that the exception is due rather to the qualitative than to the quantitative effect of brightness upon color.

color at decreased illumination; column 6 shows the limit with a white screen; and column 7 with a black screen.

TABLE XV.

A. *Showing the color limits at standard and decreased illumination (a) with gray screens of the brightnesses of the colors at the illumination used; and (b) with white and black screens.*

	Standard Illumination			Decreased Illumination		
Stimulus	Limit with gray screen of brightness of color at standard illumination	Limit with white screen	Limit with black screen	Limit with gray screen of brightness of color at decreased illumination	Limit with white screen	Lmit with black screen
Yellow	44°	42°	45°	43°	35°	43°
Green	37°	36°	34°	36°	31°	27°
Red	43°	42°	44°	40°	31°	40°
Blue	53°	50°	49°	49°	36°	43°

TABLE XVI.

Observer C.

Yellow	49°	46°	50°	46°	36°	44°
Green	44°	42°	40°	41°	28°	33°
Red	45°	41°	45°	41°	34°	41°
Blue	56°	55°	53°	50°	38°	44°

Tables XVII and XVIII to show the following facts:

(*a*) How much the decrease of illumination narrowed the limits of color sensitivity by causing a decrease in the energy of the light-waves coming to the eye. This was determined by subtracting the value of the limit at decreased illumination with the screen of a gray of the brightness of the color at decreased illumination from its value at full illumination with the gray screen of the brightness of the color at full illumination. (*b*) How much the limits were narrowed by the action of the white and black screens at decreased illumination. This was ascertained by subtracting the values of the limit with the white and the black screen at decreased illumination from the value of the limit at decreased illumination with the gray screen of the brightness of the color at this illumination. (c) How much

more the limits were narrowed by the white and the black screens at decreased than at full illumination. This was computed for the white screen, for example, as follows: The quantity, limit at decreased illumination for gray screen of brightness of color at decreased illumination, minus limit for white screen at decreased illumination, is subtracted from the quantity, limit at full illumination for gray screen of brightness of color at full illumination minus limit for white screen at full illumination. A similar computation was made for the black screen.

TABLE XVII.

A. *Showing (a) how much the limits were narrowed by decrease in the amount of colored light coming to the eye; (b) how much they were narrowed by increased induction of white and black screens at decreased illumination; and (c) how much more they were narrowed by induction of white and black screens at decreased than at full illumination.*

Stimulus	How much limits were narrowed by decrease in amount of colored light coming to the eye	How much limits were narrowed by induction of white screen	How much limits were narrowed by induction of black screen	How much more limits were narrowed by white screen at decreased than at full illumination	How much more limits were narrowed by black screen at decreased than at full illumination
Yellow	1°	8°	0°	6°	1°
Green	1°	5°	9°	4°	6°
Red	3°	9°	0°	8°	1°
Blue	4°	13°	6°	10°	2°

TABLE XVIII.

Observer C.

Yellow	3°	10°	2°	7°	3°
Green	3°	13°	8°	11°	4°
Red	4°	7°	0°	3°	0°
Blue	6°	12°	6°	11°	3°

Results when a gray screen matching the color in brightness at standard illumination is used. In these experiments a determination was made of the amount the limits of sensitivity are changed by the brightness induction caused by the alteration of

the brightness relation between stimulus and screen with decrease of illumination, when a screen is used which matches the color in brightness at standard illumination. This determination was made as follows.

An estimate was made of the amount the limits were narrowed by decrease of illumination when a screen of the brightness of the color at standard illumination is used for both standard and decreased illuminations. From this result was subtracted the amount the limits were narrowed by decrease of illumination when the screen is made in turn of the brightness of the color at standard and at decreased illumination. The difference obtained represents the value sought. It is given in Table XIX.

TABLE XIX.

A. *Showing how much the color limits were narrowed at decreased illumination by the induction of the screen which matched the color in brightness at standard illumination.*

Stimulus	Screen of brightness of color at decreased illumination	Limit	Screen of brightness of color at standard illumination	Limit	Amount limit was narrowed by change in brightness relation between stimulus and screen caused by decreased illumination
Yellow	gray no. 3	43°	gray no. 2	41°	2°
Green	gray no. 5	36°	gray no. 8	29°	7°
Red	gray no. 50	40°	gray no. 24	33°	7°
Blue	gray no. 13	49°	gray no. 28	46°	3°

(*C.*) *The Effect of These Amounts of Induction upon the Limens of Color at Different Degrees of Excentricity.*

We have shown the effect of decreasing the general illumination upon the color sensitivity of the peripheral retina with gray, white, and black screens by the effect on the limits of sensitivity. This is only an indirect means of estimating its influence, for the results obtained cannot be translated into terms of direct measurement, owing to the irregular decrease in sensitivity of

the peripheral retina from the fovea outwards. In this section, we shall measure the influence of changes of illumination directly by the changes produced in the limen of sensation at various angles of excentricity. As in the previous section, measurement will be made of the effect upon sensitivity (*a*) of the decrease in the amount of colored light coming to the eye, produced by the decrease of illumination, (*b*) of the difference in the inducing power of the white and black screens, and (*c*) of the change in the brightness relation of stimulus to background.

To determine the first of these three points, a campimeter screen had to be selected that gave no brightness contrast with the stimulus. To provide for differences in the brightness of the colors at the different points observed for the two illuminations at which we worked, a preliminary determination of the brightness of the sensation at these points was made at both illuminations by the flicker method. The brightness of the screen was chosen in each case of the brightness of the color according to these determinations. To eliminate the effect of preëxposure, the stimulus previous to exposure was in every case covered by a gray of the brightness of the color for the illumination used at the point of the retina at which we were working. Thus no brightness after-image was carried over to exert an inhibitive action upon the color sensation. The stimulus was a disc compounded of the sectors of the color, and of the gray of the brightness of the color for the illumination used at the point of the retina under investigation. The proportions of the sectors were altered until the observer gave the judgment of just noticeable color. The average of judgments made in ascending and descending series was chosen as the final value of the limen. The difference between the limens at standard and decreased illumination was taken as the measure of the loss in intensity which the stimulus had sustained by the decrease of illumination.

The effect upon the color limen of the increased induction from the white and black screens was shown by the same method, with the exception that the white and black screens were substituted for the gray of the brightness of the color. The stimulus was a disc composed of sectors of color and gray of the brightness of

the color at the angle of excentricity at which the determination was made.

The effect of the change in the brightness relation between the stimulus color and the screen produced by decrease of illumination was shown as follows. An estimate was made of the amount the limens are raised by the decrease of illumination when a screen was used for both standard and decreased illumination that had a brightness-value equal to the color at standard illumination. From these results was subtracted the amount the

TABLE XX.

A. *Showing how much the limens of sensitivity were raised at the fovea, and at points 15°, 25°, 30° from the fovea in the horizontal meridian on the temporal side by the decrease in the amount of colored light coming to the eye produced by the decrease in the general illumination.*

Stimulus	Point on horizontal temporal meridian at which limen was taken	Limen at standard illumination with screen of brightness of color at standard illumination	Limen at decreased illumination with screen of brightness of color at decreased illumination	How much limen was raised at decreased illumination
Yellow	0°	18°	20°	2°
	15°	22°	32°	10°
	25°	35°	40°	5°
	30°	50°	65°	15°
Green	0°	20°	20°	0°
	15°	27°	28°	1°
	25°	40°	50°	10°
Red	0°	9°	11°	2°
	15°	9°	13°	4°
	25°	17°	25°	8°
	30°	25°	45°	20°
Blue	0°	9°	10°	1°
	15°	10°	13°	3°
	25°	12°	15°	3°
	30°	20°	40°	20°

limens were raised by decreasing the illumination when the screens were made in turn of the brightness of the color at standard and at decreased illumination. The difference obtained represents the value sought. These results are of particular importance because they show that the influence of the brightness of the surrounding field can not be eliminated even when a screen of the brightness of the color is used unless some means be had of maintaining the general illumination of the room constant.

Table XX shows how much the limens of sensitivity were raised at the fovea and at points 15°, 25°, and 30° from the

TABLE XXI.

A. *Showing the color limens at standard and decreased illuminations with white and with black screens.*

Stimulus	Point on horizontal temporal meridian at which limen was taken	White screen		Black screen	
		Limen at standard illumination	Limen at decreased illumination	Limen at standard illumination	Limen at decreased illumination
Yellow	0°	22°	25°	28°	30°
	15°	25°	50°	35°	45°
	25°	50°	80°	65°	85°
	30°	80°	125°	95°	113°
Green	0°	22°	25°	28°	30°
	15°	30°	36°	35°	43°
	25°	50°	75°	75°	220°
Red	0°	13°	20°	10°	14°
	15°	19°	35°	15°	21°
	25°	30°	55°	23°	35°
	30°	50°	330°	29°	58°
Blue	0°	17°	22°	10°	12°
	15°	25°	40°	12°	17°
	25°	35°	60°	18°	25°
	30°	40°	90°	30°	60°

fovea in the horizontal meridian on the temporal side by the decrease in the amount of colored light coming to the eye pro-

duced by the decrease in the general illumination. The results of this table may be generalized as follows:

1. The limen of color is higher in the periphery than in the center of the retina at both illuminations.

2. The limen of color is higher at decreased illumination than at standard illumination.

3. The direct effect upon the intensity of the sensation produced by decreasing the illumination is shown by the limen determinations to be inconsiderable. In the central retina, the difference is but 1° or 2°. In the peripheral retina at the points considered there is a difference of from 10° to 20°.

Table XXI shows the color limens at both standard and decreased illuminations when white and black screens are used, at the fovea, and at points 15°, 25°, and 30° in the horizontal meridian on the temporal side.

Table XXII has been compiled from Tables XX and XXI to show how much greater the limens were for white and black screens at decreased than at full illumination; how much of the effect may be ascribed to the reduction of the amount of colored light coming to the eye; and how much to the increased induction of the screens. It will be seen from the results of this table that the loss of the sensation in intensity due to the increased brightness induction is much greater than that caused by the reduction in the amount of colored light coming to the eye.

It was shown in Table XIV that quite a great deal of brightness induction is caused by the change in brightness relation between color and screen produced by decreasing the illumination. Table XIX shows how much this induction narrows the limits of sensitivity to the four colors used. Table XXIII, shows how much the limens are raised when the illumination is decreased by the inductive action caused by the change in the brightness relation between stimulus color and gray screen of the brightness of the color at standard illumination.

Table XXII.

A. *Showing how much greater the limens were with white and black screens at decreased than at standard illumination and how much of this effect may be ascribed to the reduction in the amount of colored light coming to the eye and how much to the increased inductive action of the screens.*

Stimulus	Point on horizontal temporal meridian at which limen was taken	White screen: Total amount greater	White screen: Amount due to decrease in amount of colored light coming to eye	White screen: Amount due to increased induction of screen	Black screen: Total amount greater	Black screen: Amount due to decrease in amount of colored light coming to eye	Black screen: Amount due to increased induction of screen
Yellow	0°	7°	2°	5°	12°	2°	10°
	15°	28°	10°	18°	23°	10°	13°
	25°	45°	5°	40°	50°	5°	45°
	30°	75°	15°	60°	63°	15°	48°
Green	0°	5°	0°	5°	10°	0°	10°
	15°	9°	1°	8°	16°	1°	15°
	25°	35°	10°	25°	180°	10°	170°
Red	0°	11°	2°	9°	5°	2°	3°
	15°	26°	4°	22°	12°	4°	8°
	25°	38°	8°	30°	18°	8°	10°
	30°	305°	20°	285°	33°	20°	13°
Blue	0°	13°	1°	12°	3°	1°	2°
	15°	30°	3°	27°	7°	3°	4°
	25°	48°	3°	45°	13°	3°	10°
	30°	70°	20°	50°	40°	20°	20°

TABLE XXIII.

A. *Showing how much the color limens were raised at decreased illumination by the induction of the screens which matched the color at standard illumination.*

Stimulus	Point on horizontal temporal meridian at which limen was taken	Limen with screen of brightness of color at decreased illumination	Limen with screen of brightness of color at standard illumination	Amount limen was raised by change in brightness relation between stimulus and screen caused by decrease of illumination
Yellow	0°	20°	20°	0°
	15°	32°	32°	0°
	25°	40°	40°	0°
	30°	65°	116°	51°
Green	0°	20°	20°	0°
	15°	28°	40°	12°
	25°	50°	190°	140°
Red	0°	11°	11°	0°
	15°	13°	24°	11°
	25°	25°	48°	23°
	30°	45°	150°	105°
Blue	0°	10°	12°	2°
	15°	13°	16°	3°
	25°	15°	23°	8°
	30°	40°	55°	15°

(*D.*) *The Influence of Change of Illumination upon the Action of the Preëxposure on the Limens and Limits of Color.*

The brightness of the preëxposure exerts an influence upon the color observation because the eye carries over an after-image from the preëxposure into the color observation. If, for example, the preëxposure is to black, a white after-image is aroused which fuses with the succeeding color sensation and strongly reduces its saturation. The effect of preëxposure is especially strong in the peripheral retina because a very strong brightness after-image is aroused in the peripheral retina by a very short period of stimulation. It is very difficult for the writer to predict from the data she has at hand with regard to the effect of change of illumination upon the sensitivity of the

peripheral retina to the brightness after-image just what will be the effect of change of illumination upon the action of preexposure on the color sensitivity of the peripheral retina. But even though there be no change in the sensitivity of the peripheral retina to the brightness after-image with change of illumination, it is obvious that there will be some effect of the change of illumination because of the change in the brightness relation of the preëxposure card to the colored stimulus. In case the stimulus light is gotten by reflection from pigment surfaces, this change of brightness relation is due to the shift in the brightness of the colors produced by the change in the illumination. In case transmitted light is used as stimulus, the brightness of the stimulus color is independent of changes in illumination and will remain constant; but a change in the brightness relation of stimulus to preëxposure will occur because the preexposure will lighten or darken with change of illumination. The writer hopes to make the quantitative investigation of this point the subject of a future study. At present she can only point out that if a guarantee is wanted that the effect of the brightness of the preëxposure is eliminated from the results of the observation, the preëxposure must be to a gray of the brightness of the color and the illumination of the room must be kept constant.

The foregoing results show how strongly the changes in the illumination of the visual field influence the color sensitivity of the peripheral retina, particularly when the stimulus is surrounded by a white field. They also show that the influence of surrounding field can not be eliminated even by means of a campimeter screen of the brightness of the color unless some means be had of keeping the general illumination of the room constant. It is obvious without further comment how important it is that a method be devised to standardize this factor. The preceding experiments indicate that without this standardization, no experiment can be repeated from time to time under the same conditions relative to any one of the brightness factors that influence color sensitivity. Results thus obtained are far from comparable.

E. *Methods of Standardizing These Factors.*

We have shown in the preceding analysis of the color observation that the factors which influence the limits of color sensitivity, and which, therefore, require standardization, are the brightness of the surrounding field, the brightness of the preexposure, and the general illumination of the retina. Standard conditions require either that the influence of a factor be eliminated, or that it be reduced to a constant. We have been able to treat all three of these variable factors in one or the other of these two ways. The effect of preëxposure and campimeter screen has been eliminated and methods of measuring the general illumination and of keeping it constant have been provided.

As we have seen, the surrounding field influences the color sensation by adding brightness to the stimulus by induction. When, for example, the surrounding field is black, white is induced by contrast across the stimulus color. Since the colors all differ in brightness, the induction takes place in different amounts for the different colors. This white in proportion to its amount reduces the action of the colors on the retina. Further, a given amount of white affects to different degrees the action of the different colors on the retina. The influence of preexposure is even more important than of surrounding field. If the preëxposure is to black, white is added as after-image to the stimulus color. The effect of a black preëxposure upon the stimulus color is greater than the effect of a black surrounding field because more white is added as after-image of preëxposure than is induced by contrast from the surrounding field. Now, since brightness induction is greatest when there is maximal opposition between the inducing and induced fields, and since the brightness after-image also is most intensive when there is maximal opposition between the stimulus and the projection field, it is evident that no one screen nor preëxposure can be found that will influence each color by an equal amount. The black preëxposure and surrounding field concomitant upon work in the dark-room can be considered no exception to this statement. The influence of preëxposure and surrounding field can not be successfully eliminated in work in the dark-room. By

using one screen and preëxposure standard conditions of contrast induction and brightness after-image can be maintained only if the colors are made of equal brightness. The objections to this procedure were pointed out in an earlier section. There remains the alternative of choosing in each case gray papers of the brightness of the colored stimulus for the screen and the preëxposure. This necessitates changes of screen and of preexposure for each stimulus, but insures the complete elimination from the color excitation of all brightness influence due either to preëxposure or to stimulation of the surrounding retina. In this way alone, then, may a proper regulation of these factors be obtained for any investigation whatsoever of the sensitivity of the peripheral retina. Further, the method gives a proper basis with regard to these two important factors from which to start all investigations of the effect of achromatic conditions upon color sensitivity.

Standardization for either one of these factors, however, can be accomplished for one degree of illumination only. As the general illumination changes, the relation of the brightness of the preëxposure and of the surrounding field to the brightness of the colored stimulus changes.[47] It is obvious, then, that if standardization is to be accomplished with regard to the influence of either of these factors, some means must be devised of maintaining the general illumination of the retina constant.

In order to obtain a standard illumination, two things are necessary: (*a*) A means of controlling the illumination must be provided, which is sufficiently sensitive to cause small changes. (*b*) A method of measuring the illumination produced has to be devised; at least, a means must be secured for determining when an illumination has been obtained that is equal to a given preceding illumination. We shall first discuss the method of measurement we adopted. As stated earlier in our paper, no

[47] When the colored light used to stimulate the retina is independent of the general illumination, e.g., when it is obtained from the spectrum, from monochromatic sources, or from standard filters, these two factors alone will modify the result of the color observation. If, however, light reflected from a pigment surface be used as stimulus, a change in the illumination will in addition change the amount of colored light coming to the eye.

satisfactory means of determining the amount of daylight illumination in a room has been provided by the physicist, so there is little hope at this time of solving the problem from that side. The brightness induction of the peripheral retina, however, has been found by us to be extremely sensitive to changes in the general illumination. This phenomenon seems to provide us with a sensitive measure of these changes, while, at the same time, it represents the combined effects for sensation of the principal subjective factors that might vary from day to day. To apply the method in its most sensitive form, the inductive power of white was chosen because it is the most strongly affected by illumination changes. For example, when No. 14 Hering gray was used as stimulus and white as campimeter screen, a noticeable change was produced in the induction when the white curtain of the optics-room was pulled forward 1 cm. from a position in which its edge was directly above the long axis of the campimeter. This caused a change in the illumination of the room so small that it could not be directly sensed. Further, at 11 o'clock in the morning of a bright day in September, when a point at 25° on the nasal meridian was stimulated, Observer *A* reported that the white screen induced black across the stimulus No. 14 gray to an amount that caused it to equal in brightness 107° of black and 253° of No. 14 gray; at 2 o'clock of the same day the induction was increased until the No. 14 gray matched 150° of black and 210° of the gray; at 4 o'clock of the same day the No. 14 gray matched 180° of black and 180° of the gray.[48] Working at 25° in the temporal meridian, this observer reported at different times during one day and on different days, the wide variations shown by the following figures: 283° of black, 225°, 145°, 190°, 238°, etc. Observer *C* reported less induction, but her variations from time to time were equally great. At 25° in the temporal meridian, she found at different times 80° of black, 103°, 160°, 175°, etc. After a careful study of the phenomenon with different screens and with different stimuli, the inductive action of the white screen upon a stimulus of No. 14 Hering gray, at 25° in the

[48] This increase in the inductive action of the screen caused by the decrease in illumination, was accompanied by a shrinkage of the zones sensitive to color covering an area of 4 to 6°.

temporal meridian, was found to provide the best means of detecting changes in the illumination of the optics-room. At this point on the retina, the induction was by no means minimal, nor was it sufficiently great to cause the medium gray chosen for our stimulus to appear too dark to give a small j. n. d. of sensation.

The sensitivity of this method of detecting changes in the general illumination was compared with the sensitivity of the Sharpe-Millar portable photometer. In this photometer one of the comparison fields is illuminated by the light of the room and the other by a standard tungsten lamp enclosed in the photometer box. When the room is illuminated by daylight, the field receiving the light of the room is seen as white, while the field lighted by the tungsten lamp appears as a saturated orange. The difference in color between the two fields renders the photometric judgment difficult and makes the instrument very insensitive for daylight tests. For example, our tests showed that by the method for indentifying an illumination described in the text, a change in illumination could be detected which was produced by drawing the white curtain 1 cm. from a position in which its edge was directly above the long axis of the campimeter. But with the receiving surface of the portable photometer in precisely the same position as the stimulus screen of the campimeter, the edge of the curtain had to be moved 11.3 cm. in order that the change of illumination might be detected. Moreover, this amount of change could be detected only in case the photometric field was continuously observed while the curtain was being drawn, in which case the comparison field was observed to become slightly darkened. The judgment was made, then, in terms of a just noticeably different brightness of the field which was illuminated by the daylight, rather than in terms of a disturbance in the brightness-equality of the two fields. When, on the other hand, the judgment was made in terms of a just noticeable disturbance in the equality of the two fields, as the judgment would have to be made if the photometer were to be employed for the reproduction of any former illumination taken as standard, the curtain had to be drawn 44.2 cm. before the change could be detected. This j. n. d. represents an amount of illumination equal to 2.5 foot-candles.

The next step was to procure a means of changing the illumination of the room by very small amounts. This was accomplished by drawing the white curtain (described p. 86) across the skylight above the apparatus. The drawing of this curtain several inches made little difference in the illumination directly observable by the eye, although, as we have said, a change of 1 cm. when the edge of the curtain was directly above the apparatus, produced a noticeable change in the inductive action of the white screen.

Having thus provided ourselves with a means of producing

small changes of illumination and with a method of detecting them, we had in order to complete our work but to choose an illumination for each observer, which could be taken as standard. Since we wished to work on both light days and days of medium darkness, an average had to be chosen as our standard from the measurements obtained on a number of days ranging from light to dark, so that on bright days the room could be darkened, and on dark days it could be lightened until this value was obtained. For Observer *A* an illumination was selected which caused an induction of black across No. 14 gray stimulus viewed at 25° in the temporal meridian to an amount which caused the gray stimulus to equal in brightness 210° of black and 150° of No. 14 gray; for Observer *B* 180° of black and 180° of No. 14 gray; and for Observer *C* 145° of black and 215° of No. 14 gray. The amount of black induction was identified in each case by means of a measuring-disc made up of sectors of black paper and No. 14 gray of the Hering series.

Previous to each series of observations the illumination of the room was changed until the amount of brightness induction was brought to the value chosen as standard. It was tested at intervals during the sitting and was readjusted when necessary. Details of the method of doing this are as follows: When the white screen and the No. 14 gray stimulus had been put in place, the observer took his position and adjusted the fixation-knot in front of the motor for the 25° point on the temporal meridian. The measuring-disc set at the standard value was mounted on the motor. The observer reported whether the stimulus appeared lighter or darker than the measuring-disc, or of a brightness equal to it. If the judgment lighter or darker was given, the curtain was drawn one way or the other until the stimulus accurately matched the measuring-disc in brightness.

This method not only gives a sensitive measure of the changes of illumination of the visual field and a successful means of standardizing the illumination of a room by daylight, but it has in addition advantages for work in psychological optics not possessed by an objective standardization, could that be successfully obtained. The problem of standardization, includes more for the

psychologist than it does for the physicist, for the former has variables to take into account in addition to the changes that may take place in the energy of the stimulus. Even though the illumination of the room be made objectively constant, we should expect variations in the response of the retina to this illumination because of its own changes from time to time. Brightness contrast, for example, might be expected to vary from sitting to sitting even when the stimulus conditions are kept absolutely constant. Two factors would be concerned in these variations: changes in the inducing power of the surrounding parts of the retina, and changes in the sensitivity of the local area. These changes would take place even when the usual precautions known to the experimenter in this field have been observed. Such precautions are commonly limited to fatigue, adaptation, etc. These precautions do not provide for the changes that occur in the retina from day to day. Moreover, they do not adequately guard against a change in a factor, unless some measure of that factor be had. So far as the writer knows, in these general precautions intended to keep the state of the retina constant, no measure of the variable factor has been provided to test the adequacy of the method. The method proposed by us, however, is planned with this in view. It takes into account not only the objective, but the subjective variables, and reduces both to a constant. For example, when No. 14 gray surrounded by the white field is made equal to the measuring-disc composed of 210° of black and 150° of the No. 14 gray for Observer *A*, it means that the observation may be begun with the assurance that the total result of all the factors—the illumination of the room, the local sensitivity of the retina, and the inductive action of the surrounding parts of the retina—is the same as in the preceding observation.

What has just been said should not be considered as more than a general statement of the application of the principles of the method. In actual practice a greater refinement of working may be attained. If, for example, one wishes to use a preëxposure differing in brightness from that of the colored stimulus, and doubts whether a test which covers only the local sensitivity of the retina and the inductive action of the surrounding parts is a

sufficient check upon the after-image sensitivity, he may make his standard include the effect of the preëxposure he wishes to use. In short, if he does not consider adequate the more general test we have described, he may duplicate, in establishing his standard, any combination of brightness factors, due to preëxposure, brightness of screen, or what not, that he may wish to use in his experiment proper.

The test of a method is how well it works. The test of this method is that we shall be able closely to duplicate our results from sitting to sitting regardless of the changes in the outside illumination from day to day or from morning until afternoon. The method stands the test. Long series of observations in the peripheral retina show a very small M. V.—much less even than is shown in the ordinary color observations in the central retina where, as compared with the peripheral retina, the factors extraneous to the stimulus exert little influence.

The following table has been compiled from a number of observations to show the variations in the results of color limens and color limits (*a*) when the general illumination was controlled according to the method described above, and (*b*) when no further precautions were observed than were used by previous investigators. In previous investigations of the color sensitivity of the peripheral retina, care has been taken to work only at the same hours of days that appeared equally bright, or, if on days of different brightness, to make a rough approximation of preceding illuminations by means of curtains without using either a definite standard or means of measuring. For our work with the illumination controlled, the gray of the brightness of the color at the illumination selected as standard was used for the preëxposure and the campimeter screen. For the work without any especial control of the illumination, the gray of the brightness of the color on one of the days selected as typical was used throughout for preëxposure and screen. This gave in the first case complete elimination of the effect of preëxposure and surrounding field, and in the second case elimination as complete as could be gotten without accurate control of the general illumination. Results are given in the table for blue and green only because the sensitivity to these colors is affected most by changes of illumination.

Stimulus	Illumination	Screen and Preëxposure	Variation of limits on different days	Variation of limens on different days
Green	Controlled	Gray no. 8	0°	0° [49]
	Uncontrolled	Gray no. 9	4°-6°	60°-82° [50]
Blue	Controlled	Gray no. 28	0°	2°-3°
	Uncontrolled	Gray no. 30	4°-5°	18°-30°

At the conclusion of a piece of work the object of which has been the elimination of sources of error in one of the oldest and best developed fields of psychological investigation, the following comments having a more general application to other fields in which sensory determinations are required, may be justified. In all sensory determinations, investigators have been very much annoyed by the magnitude of the mean variation that has occurred in their results. This may be due to two sets of factors: errors in the control of the factors that influence the response of the sense-organ, and errors in judgment. To eliminate the latter source of errors, the psycho-physical methods have been devised. Before beginning her attempts to get a better control of the factors that influence the color sensitivity of the retina, the writer had used all the psycho-physical precautions known to her to eliminate errors in judgment, still her inability to reproduce her results rendered in her judgment any accurate investigation of the sensitivity of the peripheral retina hopeless. On the other hand, however, with the control she has been able to get of the factors that influence the sensitivity of the retina to color, and with only a casual observance of psycho-physical precautions, a very close reproduction of results has been rendered possible. With regard to work in the optics of color at least, then, she is forced to conclude that the major source of error is not in the factors that influence the judgment but in those that influence the response of the sense-organ. Moreover, she would suggest that if in other sensory fields more attention were paid to the factors

[49] The limen for green was taken in both cases at 25° on the temporal retina.

[50] The limen for blue was taken in both cases at 40° on the temporal retina.

that influence the response of the sense-organ and relatively less to the factors that influence the judgment, a higher degree of precision may be attained in our methods of working.[51]

[51] For a further discussion of this point, see Ferree, C. E., Transactions of the Illuminating Engineering Society, 1913, VIII.